Tsunami Evacuation Dynamics following the 2016 Kaikōura Earthquake in Christchurch and Banks Peninsula, New Zealand, to inform Tsunami Evacuation Modelling for Banks Peninsula

A thesis submitted in partial fulfilment of the requirements for the Degree of

Master of Science in Disaster Risk and Resilience

By

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Frontispiece

View from the Summit Road, Banks Peninsula looking into the Akaroa Harbour.

ABSTRACT

Recent global tsunami events have highlighted the importance of effective tsunami risk management strategies (including land-use planning, structural and natural defences, warning systems, education and evacuation measures). However, the rarity of tsunami means that empirical data concerning reactions to tsunami warnings and tsunami evacuation behaviour is rare when compared to findings about evacuations to avoid other sources of hazard. To date empirical research into tsunami evacuations has focused on evacuation rates, rather than other aspects of the evacuation process. More knowledge is required about responses to warnings, pre-evacuation actions, evacuation dynamics and the return home after evacuations. Tsunami evacuation modelling has the potential to inform evidence-based tsunami risk planning and response. However to date tsunami evacuation models have largely focused on timings of evacuations, rather than evacuation behaviours.

This Masters research uses a New Zealand case study to reduce both of these knowledge gaps. Qualitative survey data was gathered from populations across coastal communities in Banks Peninsula and Christchurch, New Zealand, required to evacuate due to the tsunami generated by the November 14th 2016 Kaikōura Earthquake. Survey questions asked about reactions to tsunami warnings, actions taken prior to evacuating and movements during the 2016 tsunami evacuation. This data was analysed to characterise trends and identify factors that influenced evacuation actions and behaviour. Finally, it was used to develop an evacuation model for Banks Peninsula. Where appropriate, the modelling inputs were informed by the survey data.

Three key findings were identified from the results of the evacuation behaviour survey. Although 38% of the total survey respondents identified the earthquake shaking as a natural cue for the tsunami, most relied on receiving official warnings, including sirens, to prompt evacuations. Respondents sought further official information to inform their evacuation decisions, with 39% of respondents delaying their evacuation in order to do so. Finally, 96% of total respondents evacuated by car. This led to congestion, particularly in more densely populated Christchurch city suburbs.

Prior to this research, evacuation modelling had not been completed for Banks Peninsula. The results of the modelling showed that if evacuees know how to respond to tsunami warnings and where and how to evacuate, there are no issues. However, if there are poor conditions, including if people do not evacuate immediately, if there are issues with the roading network, or if people do not know where or how to evacuate, evacuation times increase with there being more bottlenecks leading out of the evacuation zones.

The results of this thesis highlight the importance of effective tsunami education and evacuation planning. Reducing exposure to tsunami risk through prompt evacuation relies on knowledge of how to interpret tsunami warnings, and when, where and how to evacuate. Recommendations from this research outline the need for public education and engagement, and the incorporation of evacuation signage, information boards and evacuation drills. Overall these findings provide more comprehensive picture of tsunami evacuation behaviour and decision making based on empirical data from a recent evacuation, which can be used to improve tsunami risk management strategies. This empirical data can also be used to inform evacuation modelling to improve the accuracy and realism of the evacuation models.

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LIST OF ACRONYMS

ABM	Agent Based Model
CCC	Christchurch City Council
CCC CDEM	Christchurch City Council Civil Defence and Emergency Management
CDEM	Civil Defence and Emergency Management
Canterbury CDEM	Canterbury Civil Defence and Emergency Management
CASPER	Capacity-Aware Shortest Path Evacuation Routing
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
ECan	Environment Canterbury Regional Council
GNS Science	Geological and Nuclear Science
JMA	Japan Meteorological Agency
LCD	Least Cost Distance
LINZ	Land Information New Zealand
MCDEM	Ministry of Civil Defence and Emergency Management (now NEMA)
MMI	Modified Mercalli intensity
NEMA	National Emergency Management Agency (formally MCDEM)
NWS	National Warning System
NZCD	New Zealand Civil Defence
PTWC	Pacific Tsunami Warning Center

UC	University of Canterbury
UNDRR	United Nations Office for Disaster Risk Reduction

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1. INTRODUCTION

1.1 RESEARCH CONTEXT

Tsunami are a destructive hazard that can have devastating consequences for coastal communities, as exemplified in the catastrophic impacts of the 2004 Indian Ocean, 2006 Java, 2009 Samoa, 2010 Chile, 2010 Sumatra, 2011 Tōhoku, and the 2018 Java and Sumatra tsunami events (Power, 2013). Impact from tsunami can be categorised into two types. Primary impacts are based on the forces and the motion of the water, while secondary impacts are caused by debris flow, contaminants, and the dragging of objects and debris (Power, 2013). These impacts can have direct consequences on people, buildings, infrastructure, and the natural environment, with indirect social and economic consequences (Power, 2013). This emphasizes the need for effective tsunami risk reduction strategies. Tsunami risk management strategies can be implemented prior to a tsunami evacuation. During a response, however, the primary method to reduce risk to humans is evacuation (Jumadi et al., 2018; MCDEM, 2016; Tobin et al., 2013). This can be commenced once coastal populations have observed a natural tsunami warning, or have received an official tsunami warning (Bernard, 2005; Wei et al., 2017). For evacuations to be successful, education is required to ensure that people know how to interpret and respond to tsunami warnings and have knowledge on where and how to evacuate (Fraser, 2014; Løvholt et al., 2014).

This response strategy, however, has been limited to date by the focus and extent of research findings concerning tsunami evacuation behaviours and dynamics, with more research required in two areas. Firstly, there is limited international literature detailing the way that populations behave during tsunami evacuations (Arce et al., 2017; Fraser et al., 2016; Lindell & Prater, 2010; Makinoshima et al., 2020). A recent systematic review of 30 scientific reports and articles concerning 17 tsunami-related evacuations found that most research to date is focused on whether residents did or did not evacuate (Makinoshima et al., 2020). More empirical research is required to provide a detailed understanding of responses to warnings and tsunami notifications, and of evacuation departures, movements, and timings. These gaps mean that research to date does not allow for a "*comprehensive overview of the tsunami evacuation process*" (Makinoshima et al., 2020). This problem is exacerbated when it comes to knowledge of tsunami evacuation dynamics in New Zealand, since the rarity of tsunami in this country means there have been few opportunities to research tsunami evacuation dynamics (including Blake et al., 2018; Couling, 2014; DuBois, 2007; Fraser et al., 2016). This means that tsunami risk management in New Zealand must rely on research conducted in other countries (Jack & Schoenfeld, 2017).

Secondly, there is a lack of holistic tsunami evacuation modelling that encapsulates the behaviour of evacuees (Kubisch et al., 2019; Kubisch et al., 2020; Makinoshima et al., 2016). As identified above, literature detailing how populations behave during tsunami evacuations is limited (Makinoshima et al., 2020). This creates a gap in information available to inform evacuation modelling, with detailed evacuation behaviour information scarce, thereby reducing the accuracy of evacuee behaviour within the model (Makinoshima et al., 2016). Most evacuation models therefore exclude the variability of decisions, actions and behaviours of populations during a tsunami evacuation (Hamacher & Tjandra, 2001; Makinoshima et al., 2016), and instead, focus on the timings of the evacuees in relation to the arrival of the hazard (Makinoshima et al., 2016). Tsunami evacuation modelling has also been largely informed from reactions and behaviours reported during other hazards such as hurricanes, where the data is more readily available (Fraser et al., 2013). However, information gathered from other natural hazards do not provide applicable data for local or regional source tsunami evacuation modelling due to the short warning time during these events (Fraser et al., 2013). This issue is further exacerbated within the New Zealand tsunami evacuation modelling context. While evacuation modelling has been completed for New Zealand (Fraser et al., 2014; Knook et al., 2015) and Christchurch (Le, 2016; Power et al., 2019; Tilley, 2018) there is limited data on evacuation behaviour and responses to tsunamis in New Zealand, therefore providing few opportunities to inform evacuation modelling from empirical data. Additionally, no evacuation modelling has been performed for Banks Peninsula

This Masters research project will use a New Zealand case study to address both of these gaps in current scientific understanding of tsunami evacuation dynamics. Qualitative survey data including immediate actions following the earthquake shaking, reactions to tsunami warnings, pre-evacuation actions, evacuation dynamics, and details on congestion, will provide some of the detailed data required to inform a more comprehensive picture of tsunami evacuation behaviours. This data will be used to develop a realistic evacuation model prototype that evaluates the capacity of the roading network. The evacuation model will incorporating empirical data concerning behaviours during this real evacuation, alongside tsunami risk management strategies that have been implemented already by CCC CDEM, Canterbury CDEM and NEMA and exposure and vulnerability data.

1.2 Case Study Context

Coastal communities within Aotearoa-New Zealand are favoured locations for development, with 65% of the total population living within five kilometers of the ocean (Statistics NZ, 2006). Residential, commercial, and recreational development within these communities make coastal areas highly vulnerable to the impacts of coastal hazards including sea-level rise, inundation, and erosion (Todd et al., 2017); Tonkin & Taylor, 2017). Christchurch and Banks Peninsula, located in Canterbury on the east coast of the South Island (Figure 1.1), are highly exposed to these coastal hazards with approximately 59,510 people living in coastal suburbs (CCC, n.d.a). These coastal communities are also exposed to tsunami (Couling, 2014; Jack & Schoenfeld, 2017; Power et al., 2007).

Figure 1.1: Map of Christchurch City District.

Reducing tsunami risk through effective risk management strategies is a national priority, with significant work already being conducted in coastal communities, including Christchurch and Banks Peninsula. Approaches to date have comprised of probabilistic hazard assessment modelling for local, regional and distant sources, including detailed inundation modelling (Kohout et al., 2015; Lane et al., 2014; Lane, Kohout, et al., 2017); development of warning systems, including sirens (MCDEM, 2014); evacuation planning, including mapping of evacuation zones and route selection (CCC, n.d.b; Canterbury Maps, n.d.; Jack & Schoenfeld, 2017;); sustained education programmes (Fraser et al., 2013; Johnston et al., 2013; MCDEM, 2016); and coordinated inter-agency emergency management planning.

In 2016, a M_w 7.8 earthquake – known as the Kaikōura earthquake – generated the largest local source tsunami in New Zealand since 1947 (Power et al., 2017). The tsunami risk prompted an evacuation of coastal communities throughout New Zealand, including those in Banks Peninsula and Christchurch. Shown in Figure 1.2, a combination of natural and environmental factors created a confused warning environment to this event for those in Banks Peninsula and Christchurch (Lane et al., 2020). Founded on initial information regarding the onshore epicentre of the earthquake, the Ministry of Civil Defence and Emergency Management (MCDEM) did not believe there to be a tsunami risk to New Zealand (Power et al., 2017). The earthquake shaking that was experienced by those in Christchurch and Banks Peninsula was on the threshold of what would be expected to prompt self-evacuation. While some people did self-evacuate, many did not (Kardos, 2017). The complexity in the earthquake rupture meant the tsunami threat was not recognised until two hours after the initial earthquake shaking (Kardos, 2017). Following this, an official tsunami warning was released, and in Christchurch the tsunami sirens were activated, prompting coastal residents to evacuate (Kardos, 2017). Throughout this response, messages being received by those in Christchurch and Bank Peninsula were conflicting, making it difficult for people to assess their risk and form an evacuation decision. During this event people were unaware of their tsunami risk and lacked knowledge on the use of tsunami warnings (Kardos, 2017). A detailed overview of the response to this earthquake and tsunami can be viewed in Section 2.4.1.

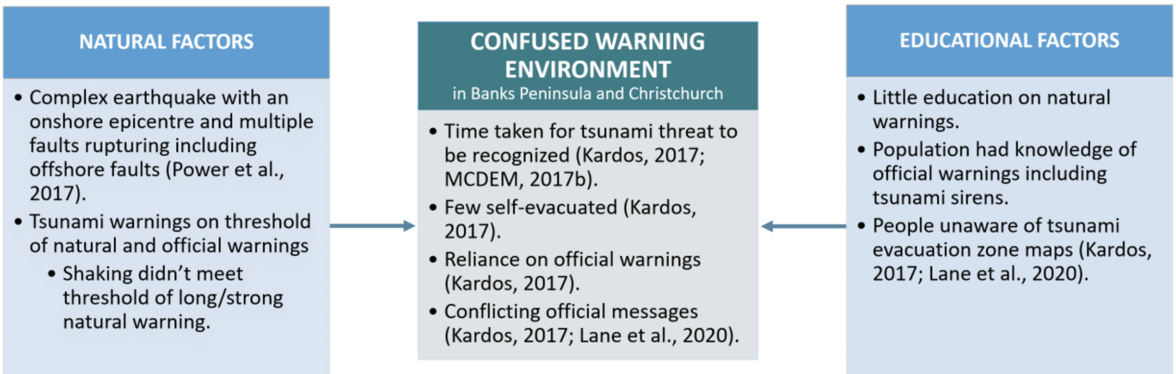

Figure 1.2: Overview of the natural and educational factors that contributed to a confused warning environment for those living in Banks Peninsula and Christchurch during the 2016 Kaikōura earthquake.

Prior to the 2016 event, there had been very few tsunami evacuations for Christchurch and Banks Peninsula, with the last major evacuation being in the 1960's (Johnston et al., 2008). Within New Zealand itself, the rarity of tsunami means that only a limited number of studies have been conducted that focus the dynamics of how people have behaved and responded during a tsunami evacuation (including Blake et al., 2018; Couling, 2014; DuBois, 2007; Fraser et al., 2016). Consequently, much of the research relating to reactions to tsunami warnings and evacuation dynamics has been conducted in other countries (Jack & Schoenfeld, 2017), and has focused on whether residents did or did not evacuate (Makinoshima et al., 2020). To date there has not been sufficient empirical evidence gathered concerning all aspects of the tsunami evacuation process to inform evidence-based tsunami risk management strategies, or to develop tsunami evacuation models that incorporate empirical evidence of human behaviour during real evacuations.

The tsunami generated during the 2016 Kaikōura earthquake provided an opportunity to gather data from Christchurch and Banks Peninsula populations concerning reactions to tsunami warnings, decision-making, and movements across all the phases of this evacuation. Assessing the evacuation dynamics associated with this event provides evidence of all aspects of the evacuation that has the potential to improve local, national and global understanding of factors that affect tsunami evacuation dynamics. This evidence, in turn, is used to develop a comprehensive tsunami evacuation model.

1.3 Research Aims and Objectives

The aim of this thesis is to enhance local and global knowledge of tsunami evacuation behaviour and reactions to warnings, which can be used to directly inform evacuation planning in the case study area (Christchurch and Banks Peninsula) and globally. Improving understanding of how people react to tsunami warnings and their evacuation behaviour during tsunami events will be achieved by utilising detailed survey responses of community members that participated in an evacuation. This survey data will provide a comprehensive overview of tsunami evacuation behaviour and decision making and can be used improve evacuation modelling by producing a more realistic evacuation model that considers evacuation behaviour rather than focusing on the timing of the evacuation. This research will help to refine evacuation planning to ensure that people can evacuate efficiently, thereby reducing their tsunami exposure and personal risk of injury and death.

The following objectives were used to achieve the research aims.

Objective 1: Identify the risk context

- Undertake a literature review to provide an overview of:
    - International, national and local tsunami risk in Christchurch and Banks Peninsula;
    - International and local tsunami risk management strategies in Christchurch and Banks Peninsula, with a local focus on evacuation, education and warnings;
    - The response of authorities to the 2016 Kaikōura earthquake tsunami.

Objective 2: Analysis of behaviour and actions to 2016 Kaikōura Earthquake and Tsunami

- Develop and distribute a survey tool to gather primary data concerning evacuation triggers, pre-evacuation actions, evacuation methods and changes in risk perception and preparedness;
- Geospatial and statistical analysis of self-reported survey data to review the reactions and behaviours of Christchurch and Banks Peninsula residents during the tsunami evacuation that took place after the 2016 Kaikōura earthquake;
- Comparative analysis of the survey data with other local and global studies;
- Characterise broad evacuation behavioral trends and show what factors were influential in evacuation behaviours and decisions.

Objective 3: Evacuation modelling

- Develop and test a modelling framework that can be used to model tsunami evacuations of Banks Peninsula's coastal communities, through the integration of:
    - Self-reported survey data on reactions and behaviours during the 2016 tsunami evacuation,
    - Exposure and vulnerability data,
    - Implemented tsunami risk management strategies;

- Use the modelling results to identify tsunami risk management strategies that could be implemented in Banks Peninsula to reduce tsunami risk by improving the efficiency of future evacuations.

1.4 Disaster Risk Management (DRM)

Tsunami risk management is a particular example of disaster risk management. The foundation of disaster risk management (DRM) is to understand the hazards, exposure and vulnerabilities of people and assets, and to use this knowledge and understanding to anticipate the impacts that may occur (GFDRR, 2014; GFDRR, 2016; The World Bank & GFDRR, 2012) (Figure 1.3). This guides priorities, plans and strategies that aim to manage the disaster risk (GFDRR, 2014).

Figure 1.3: Disaster risk function, where hazard, exposure and vulnerability all contribute to disaster risk (GFDRR, 2016).

Since 2005, significant progress has been made in understanding the components of risk. More models and tools have been developed that can be used to identify, analyse and manage, risk data (GFDRR, 2014). These tools are more freely available. There is also a deeper understanding from governments and organisations that risk needs to be managed (GFDRR, 2014).

1.4.1 Terminology

Hazard refers to a phenomenon or natural process that can cause loss of life, injury, damage to property, economic and social disruption or degradation of the environment (UNISDR, 2009). Hazards contributing to disaster risk include natural, environmental, and technological hazards (UNISDR, 2009). Hazards are described by their frequency of occurrence or intensity (UNISDR, 2009).

A **Disaster** is the disruption of a community or society due to a hazard event, which has exceeded the capacity of the community or society to cope with its own resources (UNISDR, 2009). Disasters are often considered to occur because of factors such as exposure to a hazard, vulnerability and/or an inability to reduce or cope with negative consequences. (UNISDR, 2009).

Exposure refers to people and assets such as housing, infrastructure and agricultural land that may be affected by a hazardous event (Birkmann, 2013; UNISDR, 2009). The exposure element of risk is dynamic, and changes over time while also being influenced by human activity and behaviour (GFDRR, 2014). As the population grows and the value of assets increase, exposure increases (GFDRR, 2016).

Vulnerability is the characteristics of an individual, society, or assets that determine how the individual, society, or asset may be impacted by a hazard (Cutter, 2013; UNISDR, 2009). Vulnerability includes physical and social vulnerability (GFDRR, 2016). Vulnerabilities are dynamic, influenced by humans and can change on a temporal scale (GFDRR, 2014). Urban and socioeconomic development influence vulnerability (GFDRR, 2016). For example, as living conditions improve people can become less vulnerable.

Impact refers to the effects of a hazardous event (UNISDR, 2009). Impacts are typically negative but can be positive. In the context of DRM, impact refers to what might happen to people and/or assets during a singular event (GFDRR, 2014).

Risk refers to the combination of a hazard occurring and the negative consequences that may occur (UNISDR, 2009). This can be expressed as "Risk = Hazard x Exposure x Vulnerability". Risk changes on a spatial and temporal scale as hazard, exposure, and vulnerability change. Risk can be influenced by policy decisions for example allowing activities in hazardous areas (GFDRR, 2016). Whereas impact refers to a single event, risk is the combination of all impacts from multiple events (GFDRR, 2014).

Disaster Risk Management (DRM) is the application of policies and strategies to *"improve coping capacities in order to lessen the adverse impacts of the hazards and the possibility disaster"* (UNISDR, 2009). The aim is that one or more of the components of risk (hazard, exposure, or vulnerability) are reduced, either in terms of the intensity or the frequency (GFDRR, 2016).

Disaster Risk Reduction (DRR) aims to reduce and prevent disaster risk by reducing exposure, lessening vulnerability and improving preparedness (UNISDR, 2009). DRR can also be achieved through land and environment management (UNISDR, 2009) This can be achieved through the implementation of policies, investments, and structural and non-structural measures which may be designed through knowledge and understanding of the risk and hazard (GFDRR, 2014).

Risk Perception is a personal assessment of the consequences that may be caused by a hazard (Lindell, 2013). It is largely influenced by psychological, cultural, and social aspects (Dzialek, 2013; Fraser et al., 2016).

Preparedness involves building knowledge and capacities to manage disasters (UNISDR, 2009). It can be achieved or facilitated by governments, communities, individuals, and organisations (UNISDR, 2009). To facilitate preparedness strategies, knowledge of the risk is required (GFDRR, 2014). Preparedness activities can be linked to the development of early warning systems, stockpiling supplies, contingency plans, and education and training (GFDRR, 2014; UNISDR, 2009).

Resilience is the ability of a community, society or system to *"resist, absorb, accommodate to and recover from the effects of a hazard"* (UNISDR, 2009). The resilience of a group is influenced by the resources and preparation completed prior to and during the event (UNISDR, 2009).

Risk Communication is the process in which information regarding hazards is provided or exchanged (Lindell, 2013). Primary channels for risk communication include print media, electronic media and face-to face interaction (Lindell, 2013). Effective risk communication involve stakeholders sharing information to the community (Lindell, 2013).

Education aims to assist the community in understanding their risk towards a hazard, as well as how to reduce the risk and respond effectively during an event (Johnston & Ronan, 2000). Education aims to promote long term preparedness and mitigation (Barclay et al., 2015). The primary approach in natural hazard education has been providing people with risk information, hoping that if they are informed on their risk they will take appropriate actions to reduce their risk (Barclay et al., 2015).

1.4.2 Global Disaster Risk Management

The United Nations Office for Disaster Risk Reduction (UNDRR) aims to bring "*governments, partners and communities together to reduce disaster risk and losses to ensure a safer, more sustainable future*" (UNDRR, n.d.). The UNDRR coordinates the development and UN ratification of global disaster risk reduction frameworks, and provides member nations with support to implement them. The *Hyogo Framework for Action 2005-2015* aimed to help nation states substantially reduce disaster impacts from disasters by explaining, describing and detailing the work and actions required from different sectors to reduce disaster losses (GFDRR, 2016; Satake, 2014; UNISDR, 2009). The *Sendai Framework for Disaster Risk Reduction 2015-2030* builds on the Hyogo Framework in order to bring about a *"substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries"* (UNISDR, 2015).

Adopted at the Third UN World Conference in Sendai, Japan, on March 18, 2015, this framework details high level guiding principles, and the following four Priorities for Action:

1. Understand disaster risk;
2. Strengthen disaster risk governance to manage disaster risk;
3. Invest in disaster risk reduction for resilience;
4. Enhance disaster preparedness for effective response and to *"Build Back Better"* in recovery, rehabilitation and reconstruction (UNISDR, 2015).

To achieve these four priorities, Sendai provides a disaster risk management framework consisting of five components: risk identification, risk reduction, preparedness, financial protection, and resilient reconstruction (GFDRR, 2016). These components are explained below in Figure 1.4.

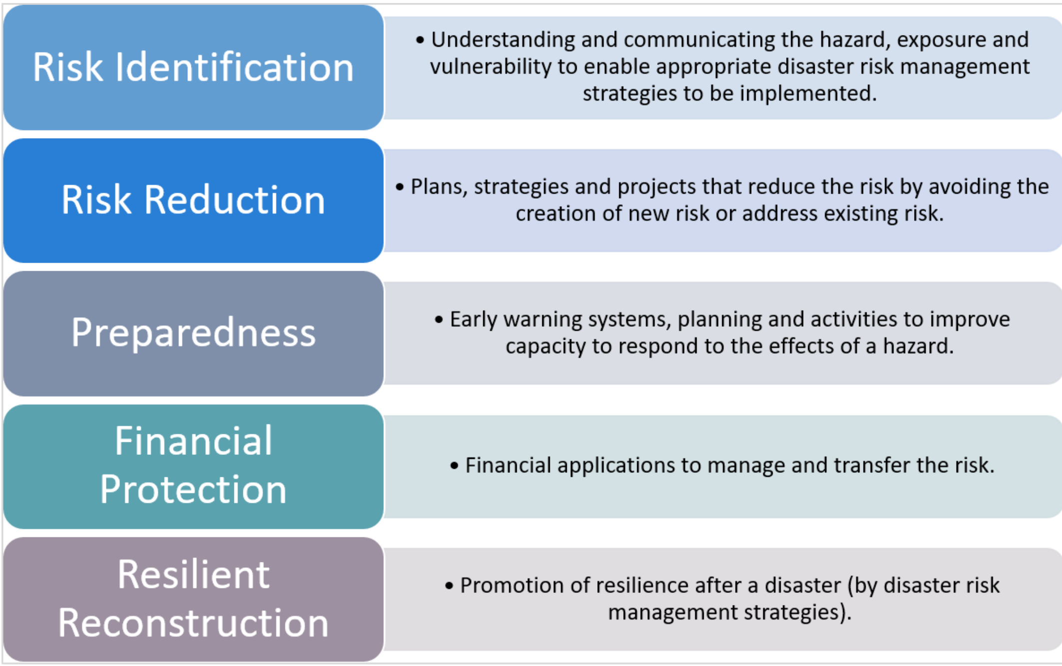

Figure 1.4: Sendai disaster risk management framework (Adapted from GFDRR, 2014; GFDRR, 2016; World Bank & GFDRR, 2012).

This Masters research contributes to risk identification, risk reduction and preparedness. Section 2 contributes to risk identification through identifying the tsunami risk within the study area and outlining the strategies that have been implemented to manage and reduce this risk. Section 3 evaluates the preparedness strategies that have been implemented. This is achieved by the analysis of behaviour and reactions during the 2016 Kaikōura earthquake. Section 4 also contributes to preparedness, but instead by outlining ways that preparedness and planning can be improved to increase the efficiency of tsunami evacuations in the future. Sections 3 and 4 contribute to risk reduction through outlining hazard and risk information that can be utilized to inform policies, investments and structural and non-structural measures with the intention of reducing risk.

1.4.3 New Zealand Disaster Risk Management

As a member of the United Nations general assembly, the New Zealand government has adopted the *Sendai Framework for Disaster Risk Reduction 2015-2030* (MCDEM, 2019a). This framework is used to guide and influence disaster risk management in New Zealand, including tsunami risk. The goal is to develop an integrated approach to manage, respond to and recover from disaster risk. This approach is structured by the 4Rs of risk reduction, readiness, response, and recovery (MCDEM, 2019a) (Figure 1.5). It relies on identifying and understanding risk, and creating campaigns to improve public awareness, as well as the adoption of early warning systems (NEMA, n.d.a).

Figure 1.5: The 4R's of reduction, readiness, response and recovery (adapted from BOPRC, n.d. & MCDEM, 2017a).

DRM within New Zealand is underpinned by various pieces of legislation including the Civil Defence and Emergency Management Act 2003, the Building Act 2004, the Resource Management Act 1991, the Local Government and Official Information & Meetings Act 1987 and the Local Government Act 2002. These legislation are implemented by a range of authorities including the National Emergency Management Agency (NEMA), regional councils, local territorial authorities, lifelines committees, and tertiary education providers and work to promote a resilient New Zealand (NEMA, n.d.b).

To connect the agencies and legislation that implement disaster risk management in New Zealand, the *National Disaster Resilience Strategy* was released in 2019. This strategy provides a "*holistic approach to resilience*" and sets out the goals and objectives that will guide the actions undertaken by key DRR/DRM stakeholders over the next 10 years in order to achieve a resilient New Zealand (MCDEM 2019a). The primary goal of the strategy is to:

> *"To strengthen the resilience of the nation by managing risks, being ready to respond to and recover from emergencies, and by empowering and supporting individuals, organisations, and communities to act for themselves and others, for the safety and wellbeing of all"* (MCDEM, 2019a).

Three priorities have been identified by NEMA in the 2019 *National Disaster Resilience Strategy* that will help achieve improve resilience (Figure 1.6). Each priority has six objectives that are designed to guide the progress of the various priorities.

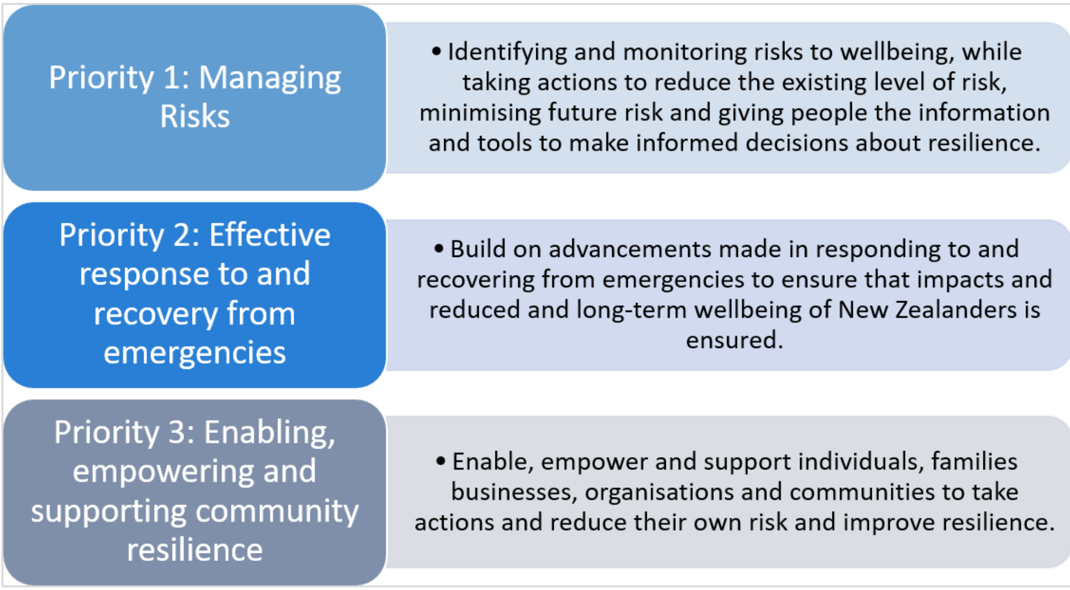

Figure 1.6: Priorities of the National Disaster Resilience Strategy (MCDEM, 2019a).

This research seeks to contribute to all three priorities that have been identified in the *National Disaster Resilience Strategy*. Section 2 contributes to managing risks by identifying the hazard component of risk while also outlining the exposure and vulnerability associated with this risk. Section 2 also details strategies of building risk awareness and risk management strategies. Section 3 contributes to managing risks by evaluating the success of risk management strategies during the 2016 Kaikōura tsunami evacuation. The findings in Section 3 also offer to contribute to effective response to and recovery from emergencies, by suggesting improvements for future tsunami response and evacuation efforts with the potential to reduce risk during future tsunami evacuations. Finally, Section 4 contributes to managing risk by identifying different exposure scenarios. Section 4 also contributes to enabling, empowering and supporting community resilience by evaluating the capacity of critical infrastructure – the roading network, and also identifying ways that individuals and communities can build resilience.

1.5 Thesis Structure

This thesis is divided into the following five chapters.

This chapter, *Chapter 1*, introduces the thesis topic, aims and objectives. It also establishes the research context for this study. First the research and case study context are outlined, followed by the aims and objectives of this research. Finally an overview of global and New Zealand disaster risk management are presented.

Chapter 2 provides a literature review. Firstly, global tsunami risk is outlined. This is followed by the tsunami risk in New Zealand with a focus on Banks Peninsula and Christchurch's tsunami risk. Following this is an overview of strategies that have been implemented at a global scale to manage tsunami risk. Next is a detailed description of tsunami risk management strategies that have been implemented to reduce the tsunami risk within Banks Peninsula and Christchurch, with a focus on warnings and evacuations. Finally, the response to the 2016 Kaikōura earthquake and tsunami is presented as the background to the case study for this Masters research. *Chapter 2* addresses Objective 1, while introducing Objectives 2 and 3.

Chapter 3 addresses Objective 2. Firstly the methodology used for the survey distribution is presented. This is followed by the survey results, which have been divided into three subsections – 'Initial Reactions', 'Evacuation Behaviour', and 'Preparedness, Risk Perception and Tsunami Knowledge'. Finally a discussion of the survey results is presented. The discussion characterises broad evacuation trends and influential factors, while drawing from and comparing to research on local and international evacuations. An overview of the limitations of the research, as well as recommendations and future work ideas are also included in the discussion. *Chapter 3* addresses Objective 2.

Chapter 4 begins with an overview of the network analyst extension tool ArcCASPER. Following this, the methodology and data used for the modelling is presented. This includes a building inventory and field observations that will be used to inform the evacuation modelling. This is followed by the results of the modelling and a discussion. The discussion focuses on the modelling results in regards to evacuation travel cost and congestion. The discussion also includes a reflection on the ArcCASPER tool, limitations of the analysis, recommendations and future work. *Chapter 4* addresses Objective 3.

Chapter 5 presents a summary of this research. This includes key findings of the evacuation behaviour survey and the evacuation modelling, following by key recommendations. Finally areas for future work are outlined.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter addresses Objective 1 of the thesis: Identify the risk context. First, the phenomenon of tsunami is explained, followed by New Zealand's tsunami risk, with a focus on the tsunami risk of Christchurch and Banks Peninsula. Next is an overview of strategies that have been implemented at a global scale to manage tsunami risk with case studies and examples provided. This is followed by a description of the tsunami risk management strategies that have been implemented in Christchurch and Banks Peninsula. Finally, the Kaikōura earthquake in 2016 and the response to the tsunami generated in this event are explained, providing context case study prompting this research.

2.2 TSUNAMI RISK

Tsunami are generated when a large volume of water has been displaced, usually by a large coastal or submarine earthquake, but can also be generated by a volcanic eruption, coastal or underwater landslides, or from a bolide impact (Leonard et al., 2011; Power & Leonard, 2013) (Figure 2.1). This produces a wave or a series of waves that propagate across the ocean at speeds over 500 kilometers per hour (Power, 2013; Power & Leonard, 2013).

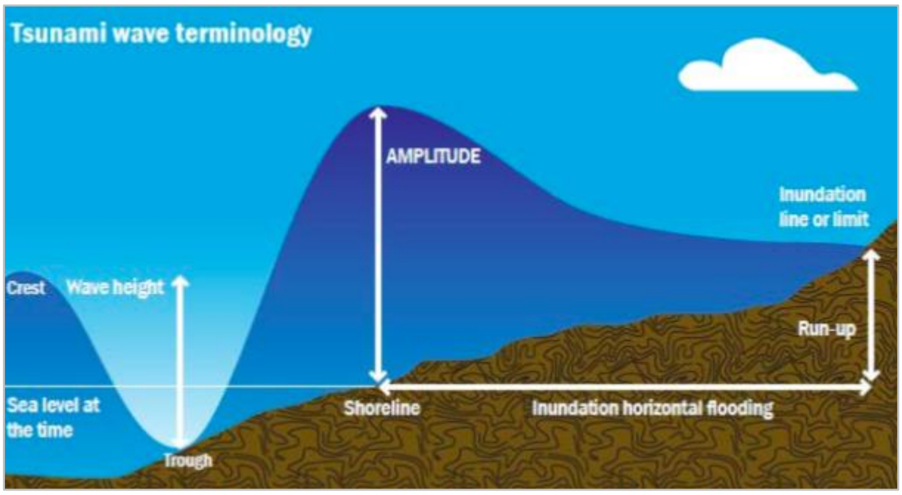

Figure 2.1: Tsunami wave terminology (MCDEM, 2016).

The behaviour of tsunami waves differs from coastal wind-derived waves (Figure 2.2) In wind-derived waves, the wave energy is limited to the ocean surface, and as the wave breaks on the shoreline the energy rapidly dissipates (Leonard et al., 2011). In a tsunami wave however, the wave energy affects the entire water column from the surface to the ocean floor. The energy in tsunami waves does not dissipate readily and instead is pushed upwards, which, once at the coastline, allows the wave to travel inland (Leonard et al., 2011). As the time between tsunami wave crests can vary from minutes to hours, tsunami waves can arrive up to hours apart without the complete retreat of the previous waves

(Power, 2013). It is important to note the first tsunami wave that may reach the shore may not be the largest.

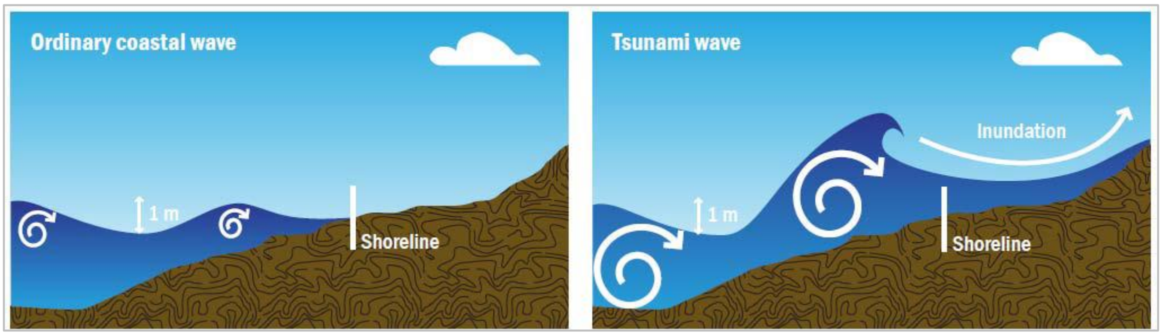

Figure 2.2: Comparison of wind derived coastal waves and tsunami waves (MCDEM, 2016).

Tsunami are destructive, inundating coastlines, causing damage to property and infrastructure, as well as resulting in a loss of economic capital, injury, and loss of life (Power, 2013). In the past two decades, 13 deadly tsunami have resulted in approximately 250,000 deaths and almost $265,000 million USD in damages (Table 2.1). The main causes of death during a tsunami are drowning, being swept away by water, and impact from debris (Power, 2013).

Table 2.1: Historical tsunami over the past 20 years with recorded casualties and damages. Where the damage is unknown, a question mark is present (NOAA, n.d.).

Year	Location	Cause	Causalities	Damage ($ Mill)
2001	Peru	Earthquake	26	?
2004	Indian Ocean	Earthquake	227,899	10,000
2006	Java	Earthquake	802	55
2007	Solomon Islands	Earthquake	50	?
2007	Chile	Earthquake & Landslide	8	?
2009	Samoa	Earthquake	192	2,200
2010	Chile	Earthquake	156	30,000
2010	Sumatra	Earthquake	431	39
2011	Japan	Earthquake	18,434	220,085
2013	Solomon Islands	Earthquake	10	2
2015	Chile	Earthquake	8	600
2018	Sulawesi	Earthquake triggered under-water landslide	3,879	912
2018	Java and Sumatra	Volcanic eruption triggered landslide	437	?

2.2.1 New Zealand Tsunami Risk

Coastal regions are favored locations for human settlement, with 65% of New Zealand's population living within 5 kilometers of the coast (Statistics NZ, 2006). As a result, coastlines throughout New Zealand have been developed for residential, recreational and commercial purposes. These assets, and the people that interact with them, are highly exposed to tsunami that may be generated off the New Zealand coast or across the Pacific Ocean (Power, 2013). It has been estimated that on average once every 10 years tsunami with run-up heights of one or more meters have affected parts of the New Zealand coastline (Power, 2013). While all coastlines throughout New Zealand are exposed to tsunami, some are at higher risk than others due to their proximity to seismic activity (Power, 2013).

Extensive work has been done to assess New Zealand's tsunami hazard. This is fundamental in understanding New Zealand's tsunami risk and informing risk management strategies. Hazard assessment requires knowledge about the hazard, including potential source mechanisms, wave height, run-up height, inundation extent, flow velocity, and flow depth (Fraser, 2014). The simplest approach, as outlined by Fraser (2014), is to map run-up and inundation extents from previous events. This could be informed from historical tsunami records or from paleo-tsunami deposits.

It has been identified that tsunami posing risk to New Zealand can be generated by local offshore earthquakes, large earthquakes along the rim of the Pacific Ocean or north of the Tonga-Kermadec Trench, as well as submarine volcanoes, and submarine and coastal landslides (Couling, 2014; Power, 2013). These tsunami can be classified by their travel time from the source to the impact location, and can be broken down into three sources:

- *Local source*. This includes the Hikurangi subduction zone and the Fiordland-Puysegur subduction zone. Estimated travel time is zero to sixty minutes to the nearest New Zealand coast;
- *Regional source.* These tsunami originating from the Puysegur trench and southwest and northeast of New Zealand. Travel time ranges from one to three hours;
- *Distant source.* This includes tsunami generated from the subduction zones that surround the Pacific Ocean. The South American coastline is the most frequent source. Travel time to reach the New Zealand coast is more than three hours (Blake et al., 2018; Fraser, 2014; Fraser et al, 2016; Power, 2013) (Figure 2.3).

A report synthesizing New Zealand's tsunami risk, including details on the frequency of tsunami and detailed hazard assessment, has been compiled by Power (2013).

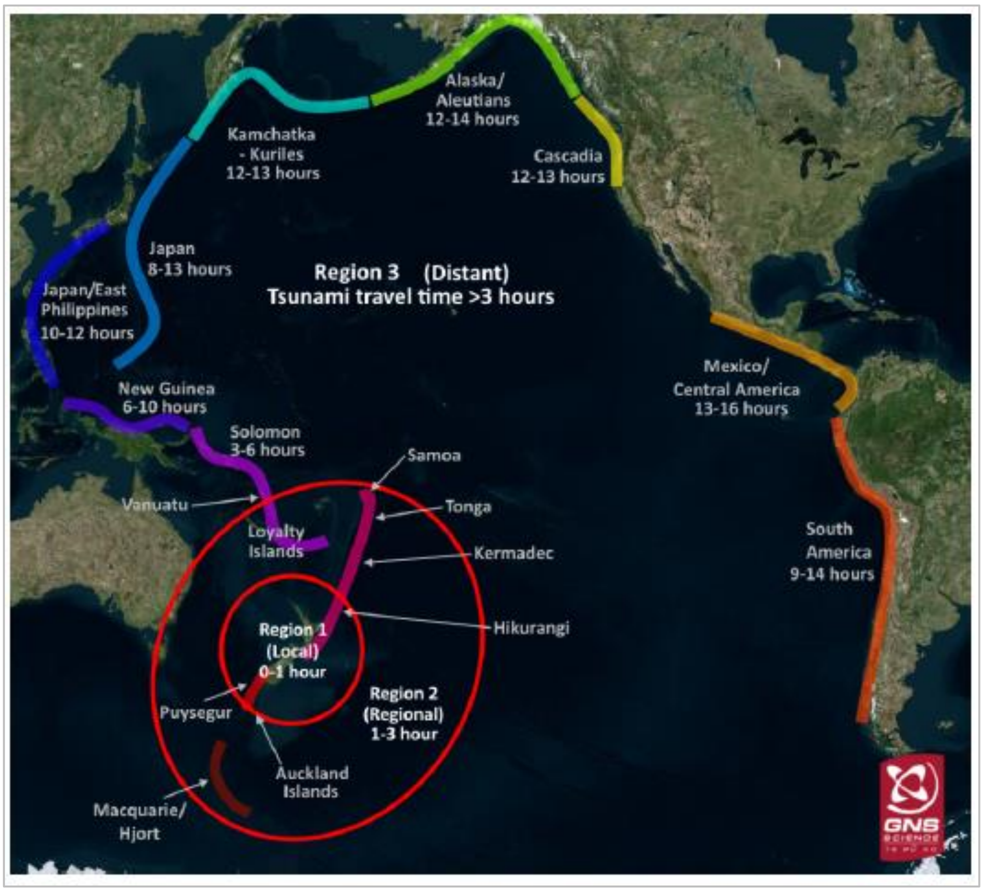

Figure 2.3: Origin of tsunami that New Zealand is exposed to (MCDEM, 2018a). Region 1 represents local source tsunami. Region 2 is regional source tsunami. Region 3 is distant source tsunami.

Individual databases have been compiled to record the historical and modern tsunami that have been observed in or impacted New Zealand (Downes et al., 2017), and paleo-tsunami deposits (Goff & Chagué-Goff, 2012).

The historical tsunami database has been compiled from oral records, written records including diaries, newspapers, and scientific reports and papers, and instrumental records including tidal gauges (Downes et al., 2017). Between 1835 and 2010, New Zealand had been affected by at least 80 tsunami. Of these, 27 originated from distant source earthquakes, 12 from regional earthquakes, 28 from local earthquake sources and 13 originated from unknown sources (Downes et al., 2017). Figure 2.4 shows the location of historical tsunami throughout New Zealand with the proximity of the tsunami source. The east coast of the North Island has predominately been affected by distant and local source tsunami. Nelson and Fiordland have been affected by local source tsunami. Northland and the Bay of Plenty have been impacted by primarily distant source tsunami, with some regional source tsunami. All other areas of New Zealand have primarily been affected by distant source tsunami.

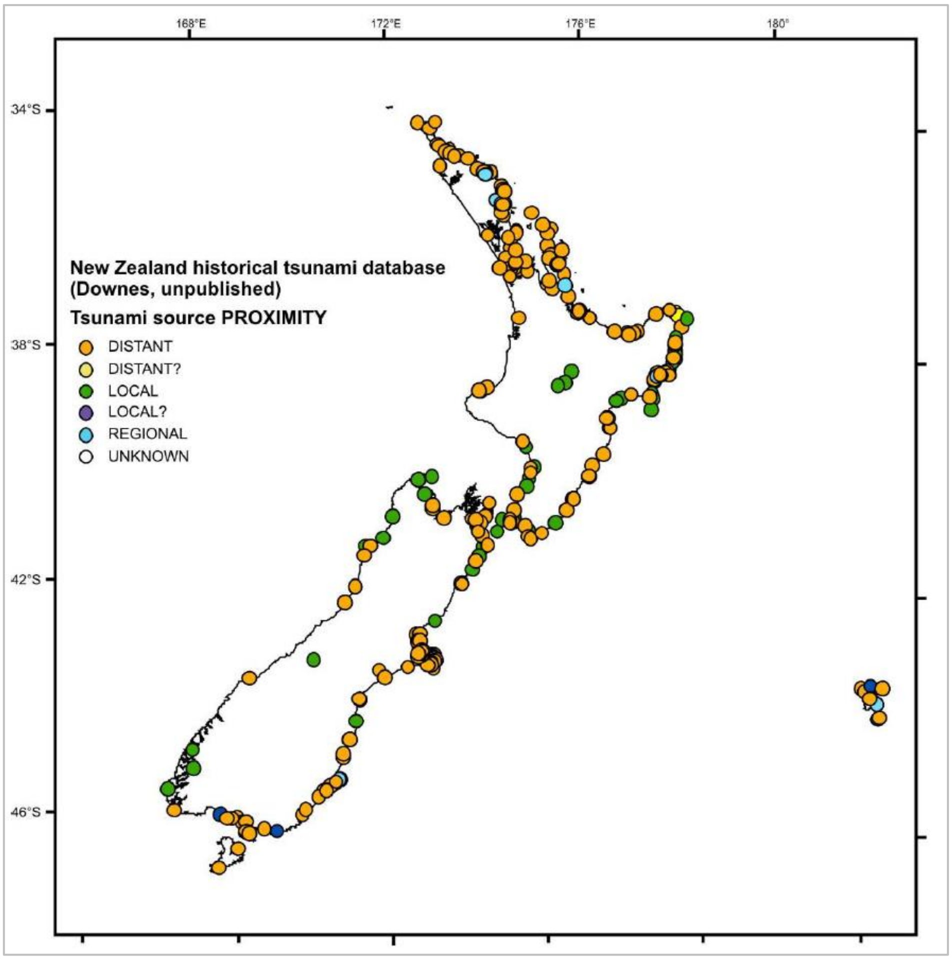

Figure 2.4: Sources of tsunami that have affected New Zealand since 1835 (Power, 2013). Note that some tsunami events may have affected multiple areas of the coastline.

The paleo-tsunami database has records for approximately 25 - 40 tsunami (Goff et al., 2010). Within this are 293 observations contributing to these records (Goff et al., 2010; Power, 2013). Most of the entries within this database have no written records or occurred prior to the historical record. Evidence for the paleo-tsunami deposits come from sediments and debris that were deposited in the coastal zone (Power, 2013). Paleo-tsunami records are useful for improving tsunami knowledge as they provide details on past inundation, source of the tsunami, and frequency and magnitude information (Power, 2013). Figure 2.5 shows the distribution of paleo-tsunami throughout New Zealand, where the location has been graduated by the validity of the data (Power, 2013).

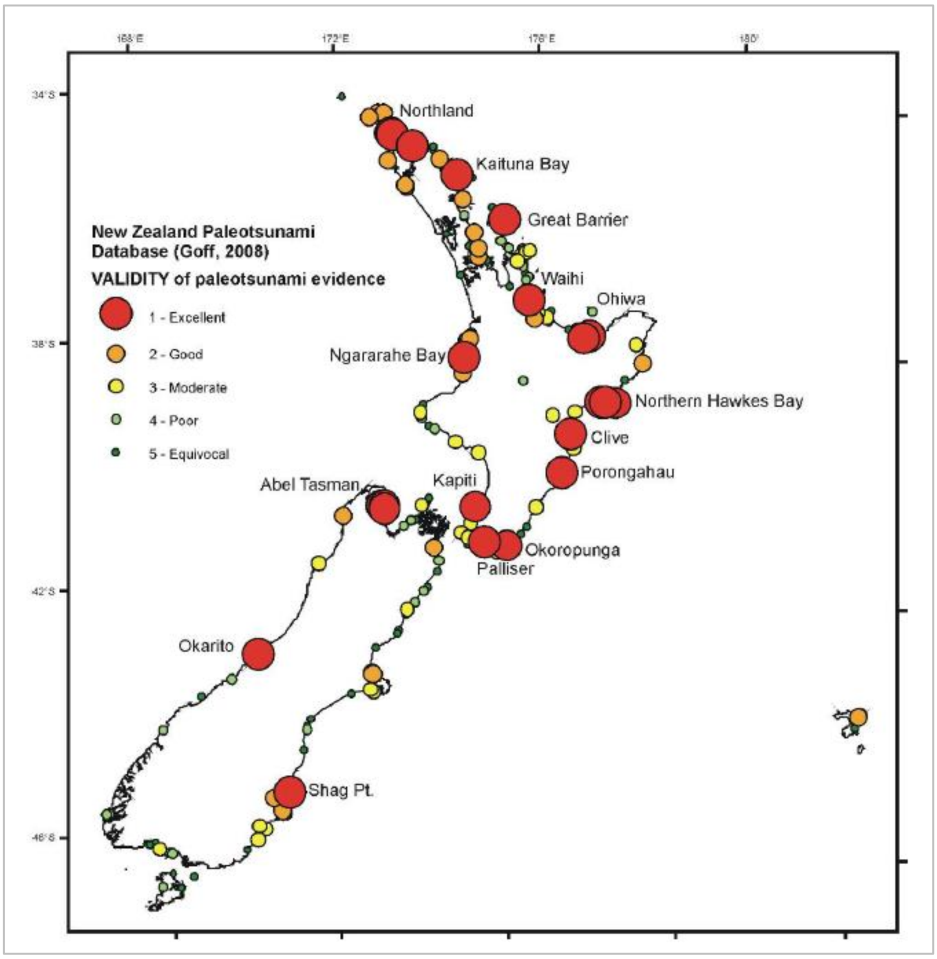

Figure 2.5: Distribution of paleo-tsunami throughout New Zealand (Power, 2013). The location of the deposits has been graduated by the validity of the data.

An example of a distant source tsunami causing damage throughout New Zealand includes a tsunami originating from South America in 1868. This tsunami impacted areas around New Zealand including Great Barrier Island, Chatham Islands, Canterbury, Oamaru, Napier, and Bay of Plenty (Power, 2013). Rup up heights of 1-4 meters were recorded throughout New Zealand and up to 10 meters in the Chatham Islands (Power, 2013). Significant damage was reported for houses, shops, wharves, boatsheds, and boats throughout the eastern coast of New Zealand, while dwellings on the northwest coast of Chatham Island were washed away (Power, 2013).

A major tsunami threat to New Zealand is posed by the Hikurangi subduction zone. Described as "*the most important local-source tsunami hazard posed to New Zealand"* (Power, 2013, p.111), the Hikurangi margin is capable of producing earthquakes greater than M_w 9.0 which may generate tsunami waves that have the potential to impact the eastern coast of New Zealand (Fraser et al., 2016). It is estimated that in an event such as this, tsunami waves may have very short arrival times of less than 10 minutes at Wellington, Gisborne and Marlborough, while the minimum estimated travel time to Christchurch is 51-60 minutes (Fraser et al., 2014; Fraser et al., 2016).

2.2.2 Christchurch and Banks Peninsula Tsunami Risk

The entire Canterbury coastline is exposed to tsunami that may be generated off the New Zealand coast and across the Pacific Ocean (Jack & Schoenfeld, 2017). Archaeological and geological knowledge, along with oral history, reveal that up to seven paleo-tsunami may have affected the region over the past 6500 years BP, with the most likely source for the majority of these being distant source tsunami originating from the Central and South American coastlines (Goff & Chagué-Goff, 2012). There is evidence of an additional three paleo-tsunami reaching northern Banks Peninsula, dated between 700 AD and 1300-1400 AD (Power et al., 2017). There is also evidence of eight historical tsunami affecting Christchurch and Banks Peninsula occurring between 1868 and 2016 (Table 2.2).

Table 2.2: Historical tsunami that have been recorded in Banks Peninsula and Christchurch (Goff & Chagué-Goff, 2012; Power et al., 2017; Williams 2016).

Year	Source
1868	South America
1877	South America
1960	South America
1964	Alaska
2010	South America
2011	Japan
2015	South America
2016	Kaikōura (New Zealand)

This knowledge of paleo and historical tsunami, along with extensive efforts to characterize the tsunami hazard through inundation modelling (Kohout et al., 2015; Lane et al., 2014; Lane, Kohout, et al., 2017; Mueller et al., 2019), identifies that Christchurch and Banks Peninsula are at risk of local, regional and distant source tsunami (Figure 2.6):

- *Local source.* While there are no known local tsunami sources, there is a possibility that an offshore earthquake fault or an underwater landslide in Pegasus Bay or the Canterbury Bight could cause damage at the heads of Banks Peninsula;
- *Regional source.* Large earthquakes generated off the Hurunui or Kaikōura coasts, the Cook Strait, the Fiordland coast or the eastern North Island coast (including the Hikurangi and Kermadec subduction zones) could generate a tsunami that may flood the heads of Banks Peninsula and low-lying areas in Christchurch;
- *Distant source*. Large earthquakes generated in or across the Pacific Ocean have the potential to cause tsunami that could affect Christchurch and Banks Peninsula (Jack, 2019; Jack & Schoenfeld, 2017).

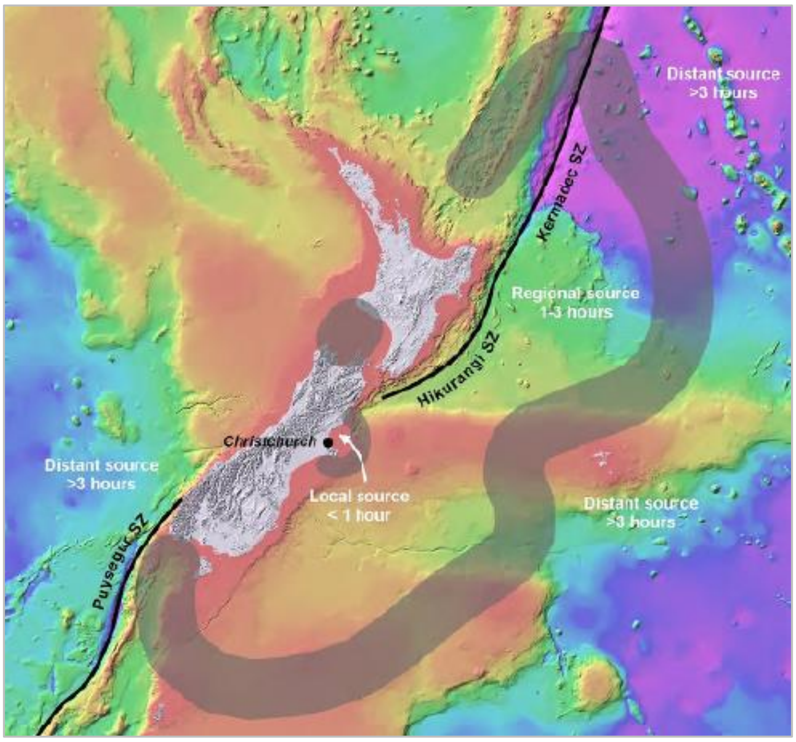

Figure 2.6: Origin of local, regional and distant source tsunami that Canterbury is at risk of (Jack, 2019).

The Canterbury coastline is at risk from all three tsunami sources (local, regional, and distant). Whereas the worst case scenario for most areas of New Zealand is a regional or local source tsunami, the Canterbury coastline is unique in that regional and distant sources contribute to the worst case category (Mueller et al., 2019). This consists of tsunami generated from:

- Hikurangi subduction zone – Mw 8.9;
- Kermadec plate interface – Mw 9.3;
- Peru – Mw 9.35 (Mueller et al., 2019).

A combination of regional and distant sources contributing to a worst-case scenario is thought to be due to the channeling effect from the Chatham Rise or the focus effect of Pegasus Bay (Mueller et al., 2019). Other distant source tsunami originating from South America are also considered to be in the worst case scenario for Christchurch and Banks Peninsula (Mueller et al., 2019). Of these sources, it has been identified that tsunami generated from large earthquakes off the coast of Peru are the biggest risk (Jack, 2019; Jack & Schoenfeld, 2017; Lane, Kohout, et al., 2017; Mueller et al., 2019). These are also the most frequent source of tsunami that have been identified or recorded throughout Banks Peninsula and Christchurch.

It has been estimated that a distant source tsunami originating from Central or South America (with a return period of 2,500 years) could generate wave heights between 6-15 meters at the coast of Christchurch (Jack, 2019) with similar wave heights around Banks Peninsula (Jack & Schoenfeld, 2017). This has the potential to flood significant areas of Christchurch and Banks Peninsula. For a tsunami such as this, while a natural warning would not be felt or observed, there would be time to undertake a managed evacuation to reduce the risk of coastal populations (Jack & Schoenfeld, 2017). Figure 2.7 shows inundation depths that have been modelled for the Akaroa Harbour from a South American tsunami source. This displays that there would be extensive inundation throughout many of the bays, including the main road of Akaroa (Lane et al., 2014)

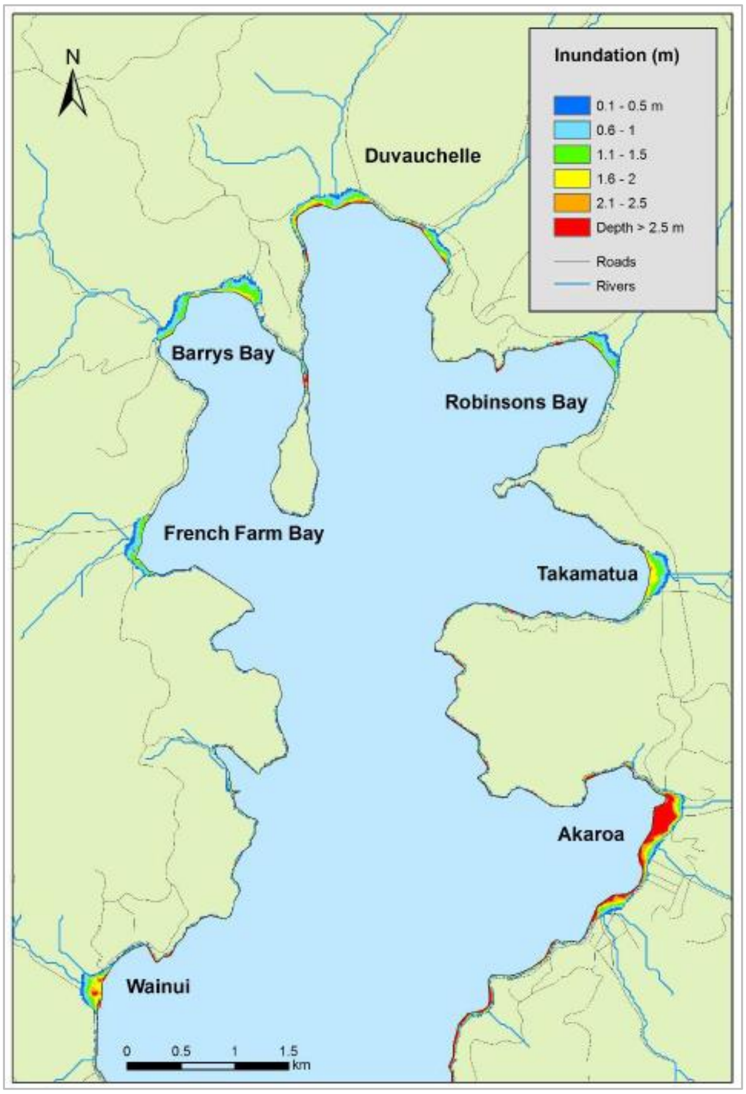

Figure 2.7: Maximum inundation depth for the Akaroa Harbour (Banks Peninsula) modelled for a South American tsunami (Lane et al., 2014).

Inundation from regional source tsunami threats have been modelled for Christchurch and Banks Peninsula. Modelling completed by Kohout et al. (2015) demonstrates that a tsunami generated from the Hikurangi subduction zone could inundate low lying coastal areas of Akaroa and Takamatua, with parts of State Highway 75 also flooded. This modelling scenario also showed inundation around Lyttleton and Teddington, including some of the low lying roads. Further modelling has been completed for Christchurch, with the results of this summarized by Jack (2019). The results of this updated inundation modelling showed that a Hikurangi scenario may generate wave heights between

2-8 meters, while a Kermadec scenario may have 7-12 meters wave heights. These scenarios show significant inundation in parts of Christchurch (Figure 2.8).

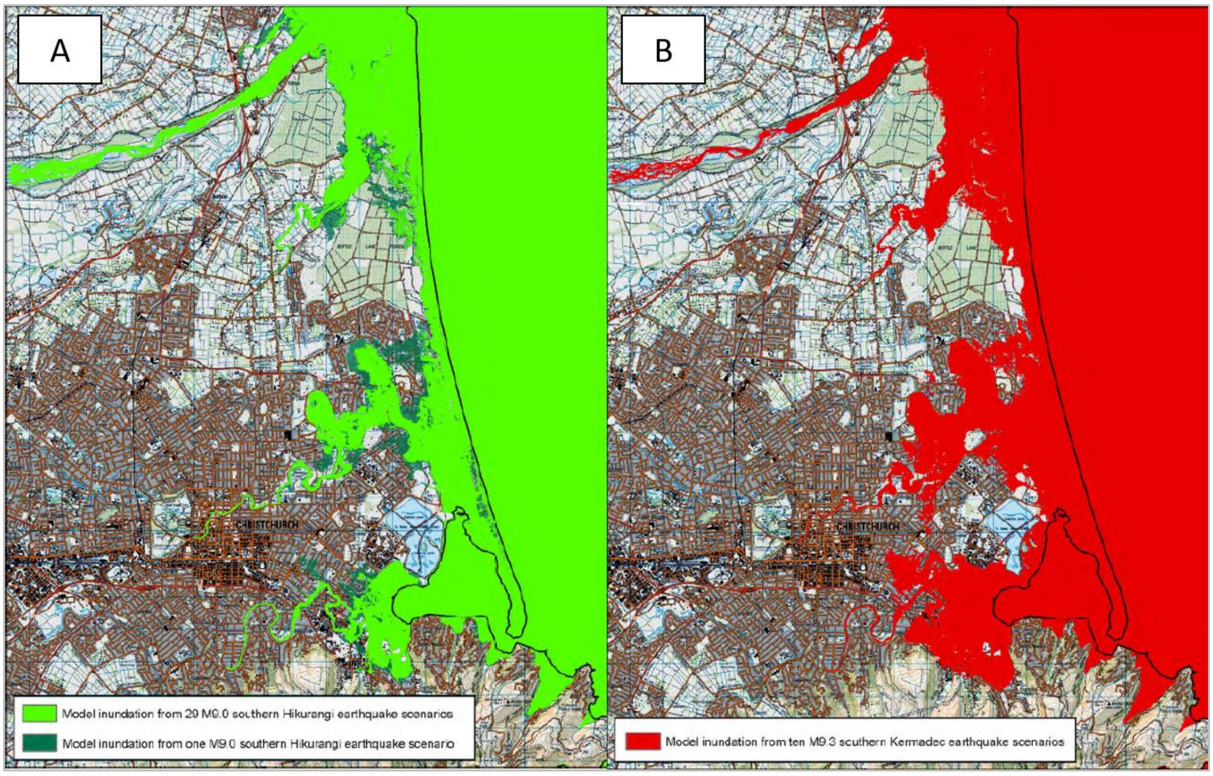

Figure 2.8: Modelled inundation extent for Christchurch from two regional source tsunami (Jack, 2019). Image A represents a compilation of 29 Mw9.0 Hikurangi earthquake scenarios in the light green and one Hikurangi scenario with a 2,500 year return period. Image B represents 10 Mw9.3 Kermadec earthquake scenarios.

Whereas much of New Zealand has had limited research completed relating to tsunami vulnerability assessments, numerous studies have been completed for Christchurch contributing to this field. The impact of tsunami on infrastructure, and habitability and displacement has been studied for areas of Christchurch, along with evacuation modelling. Scheele et al. (2020) developed a model to estimate habitability, human displacement, and sheltering needs following a tsunami in suburbs of eastern Christchurch for three inundation scenarios. The results varied with time, reflecting the response and recovery to the tsunami. For the largest scenario 14,695 residents were displaced, while 1,795 of these residents required shelter (Scheele et al., 2020). On the fourth day of the response this reduced to 9,014 displaced residents, and 4,366 residents on the seventh day (Scheele et al., 2020). Williams et al. (2020) developed an impact assessment to assess the damage likelihood for infrastructure in eastern Christchurch from a large tsunami inundation scenario. Energy, water, telecommunication, and transportation assets were included in the study. Results found that above ground assets and buried storm water pipes performed poorly and had a high damage potential, while buried potable and waste water pipes had a lower potential for damage (Figure 2.9) (Williams et al., 2020). Damage to the roading network was worse in coastal valleys, which has the potential to isolate areas like Sumner and Redcliffs (Williams et al., 2020). Evacuation modelling has been completed for pedestrian, vehicular, and public transport tsunami evacuations in Sumner (Le, 2016). The results of this estimated that it would take a maximum of two minutes to evacuate by car, and up to 20.5 minutes evacuate by foot (Le, 2016). The results stressed the importance of public transport during an evacuation which can provide transportation to population groups who may have low-mobility and lack the means to evacuate. Evacuation modelling completed by Tilley (2018) reported that the road network around Southshore, South Brighton, and New Brighton would experience significant traffic flows during a tsunami evacuation. This would lead to congestion that could contribute to evacuation times of over 100 minutes (Tilley, 2018). Further details on work completed by Le (2016) and Tilley (2018) are presented in Section 2.3.2.3.1.

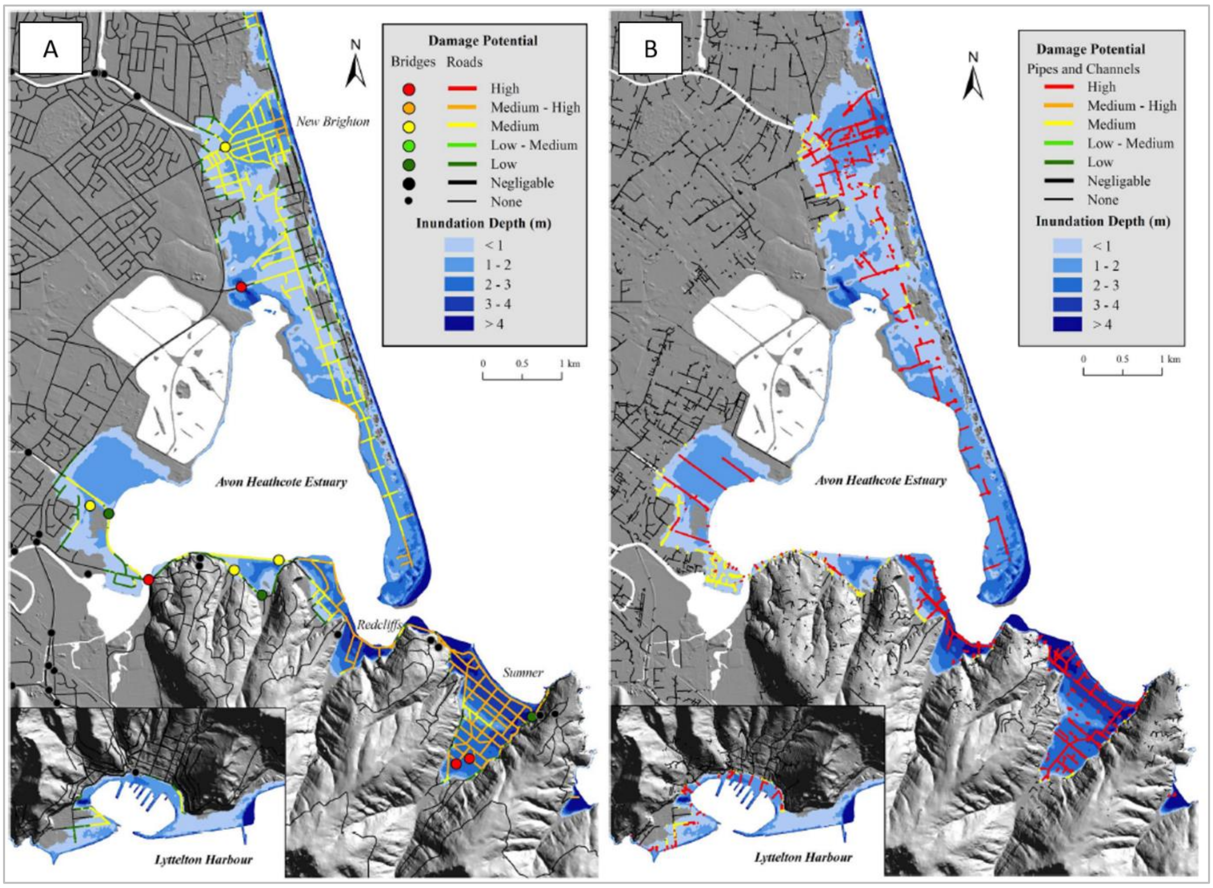

Figure 2.9: Tsunami damage potential for roads and bridges (A) and storm water network (B) in coastal communities of Christchurch (Williams et al., 2020).

2.3 TSUNAMI RISK MANAGEMENT

Coastal regions are favoured locations for human development and settlement (Power, 2013). In 2017, 600 million people – around 10% of the world's population – lived in coastal areas less than 10 meters above sea level (United Nations Ocean Conference, 2017). These areas are highly exposed to coastal hazards including tsunami. Due to the popularity of these coastal regions, it is critical that tsunami risk is managed effectively to reduce the impact of future events.

An effective way to manage a known tsunami risk is through an integrated approach (Smart et al., 2016). **Land-use planning**, as a long term strategy, can be utilized to avoid tsunami risk. If the tsunami risk is viewed as acceptable and the development of coastal locations occurs – as seen in many coastal locations around the world – short term tsunami risk management strategies can be adopted. This includes **structural** and **natural mitigation** that primarily act to reduce the risk of damage to land, property, and infrastructure. **Warning systems** and **education** can be used to reduce the risk to humans, while **evacuation** is then used as a risk management strategy during a tsunami response. These terms are explained further below.

2.3.1 Global Strategies for Tsunami Risk Management

2.3.1.1 Land-use Planning

Land-use planning is a collaborative policy-based approach that allows for the sustainable development of land (Fraser, 2014). It is a key strategy in tsunami risk management that aims to reduce the long-term risk of tsunami by guiding future development (Eisner, 2015). Plans, zoning, and regulations can be used to control the density, location, and types of development in coastal areas which help to reduce development and minimize future losses (Eisner, 2015). Due to the appeal and value of coastal land, combined with the fact that most coastal locations have already been developed, land-use planning has rarely been utilized to manage tsunami risk (Fraser, 2014; Power & Leonard, 2013). A recent exception to this trend occurred in Japan. Following the devastation and loss of life caused by the 2011 Tōhoku earthquake tsunami, legislative changes were made to ensure that land vulnerable to tsunami would not be developed for residential purposes, however, could still be utilized for recreational, agricultural, or industrial purposes (Strusińska-Correia, 2017). Figure 2.10 shows an example of land use changes following the 2011 Tōhoku earthquake tsunami.

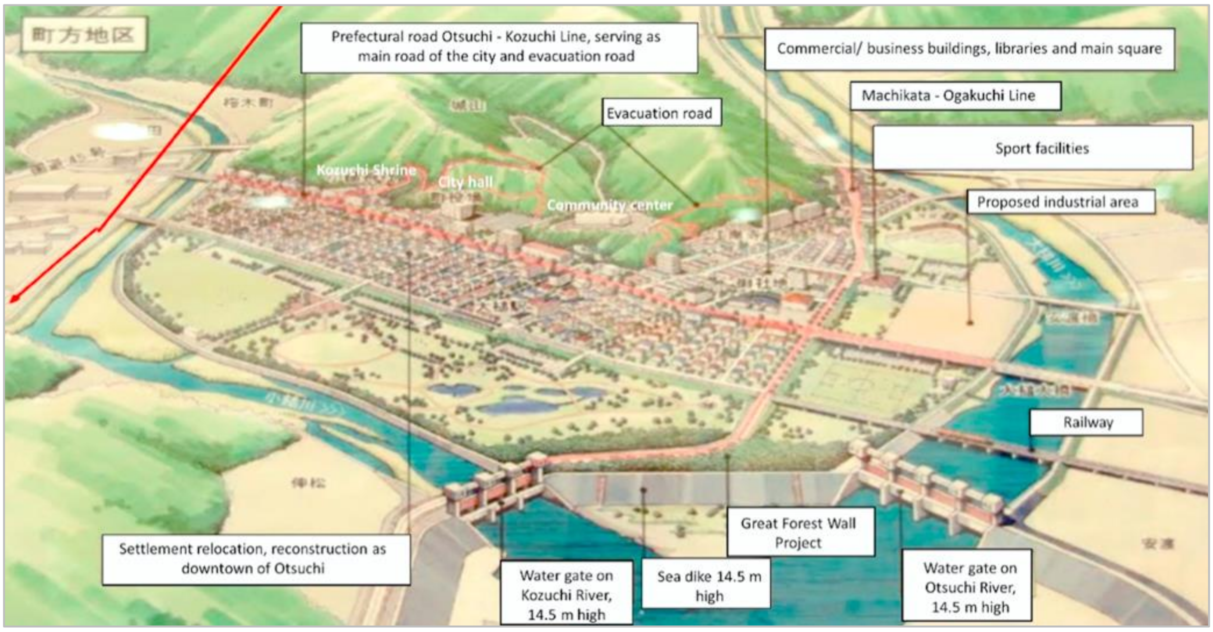

Figure 2.10: Reconstruction plan of Otsuchi, Iwate Prefecture (Japan) reflecting legislative changes in land use planning following the 2011 Tōhoku tsunami (Strusińska-Correia, 2017).

2.3.1.2 Structural Mitigation

Structural mitigation involves the development of barriers that are constructed to lessen the effects of waves (Fraser, 2014; Power & Leonard, 2013). Examples include sand dunes, seawalls (Figure 2.11), groynes, and breakwaters (Fraser et al., 2012; Power & Leonard, 2013; Suppasri et al., 2013). Typically structural mitigation strategies are constructed to mitigate against storm waves, and are rarely built to defend against tsunami. There are some defences in Japan, however, that have been constructed and designed to resist tsunami. This includes the Kamaishi breakwaters and the Tarō seawall (Fraser, 2014; Fraser et al., 2012). In order to design structures that can withstand anticipated tsunami wave heights, knowledge of the tsunami risk is required. If this knowledge is absent or inaccurate, it is possible for a tsunami wave to overtop the structural measures that have been implemented (Kitamura et al., 2020). This occurred in Kamaishi and Ofunato cities of Japan (Figure 2.12), where the 2011 Tōhoku tsunami was larger than the breakwaters were designed for (Suppasri et al., 2013). Consequently, the breakwaters were damaged and the cities inundated, however, the overall damage was reduced by the breakwaters (Suppasri et al., 2013).

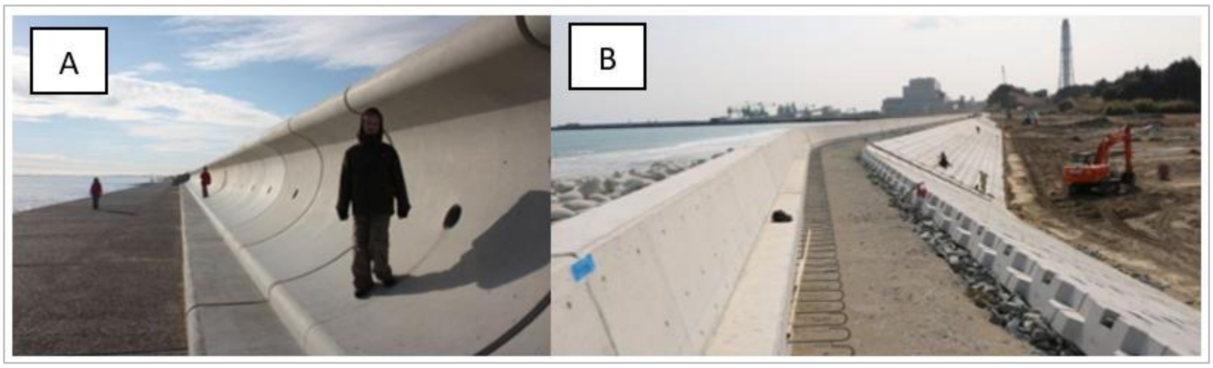

Figure 2.11: Example of a curved seawall (A) and a mound seawall (B) (Rahardjo et al., 2018).

Figure 2.12: Tsunami breakwaters in Kamaishi city and in Ofunato city (Suppasri et al., 2013). Note that these images were taken prior to the 2011 Tōhoku earthquake tsunami

The development of structural mitigation measures are expensive, requiring time and community and government consultation, while the measures themselves are disruptive to industries such as tourism and fishing (Kitamura et al., 2020). Despite their ability to reduce tsunami wave energy, structural mitigation can induce a false impression of safety and may contribute to lowering tsunami risk perception in an area (Fraser et al., 2012). It is therefore important that education and awareness about the structural mitigation defences, including that they do not bring guaranteed safety, is incorporated alongside this strategy (Fraser et al., 2012).

2.3.1.3 Natural Mitigation

Coastal and marine ecosystems such as mangroves, coral reefs, and sand dunes are examples of natural mitigation that protect against the impacts of tsunami (Tanaka, 2009). While these strategies cannot completely stop a tsunami, they can help to reduce the tsunami energy and protect shorelines from tsunami damage (Kerr & Baird, 2007; Tanaka, 2009). For example, natural mitigation can act as a buffer zone to trap debris that may be caught up in the tsunami wave (Tanaka, 2009). The Phang-nga province of Thailand was one of the most affected areas during the 2004 Indian Ocean tsunami. Mangroves along the shoreline, shown in Figure 2.13, helped to mitigate the impact of the tsunami by acting as a barrier and reducing the tidal energy to minimize damage to property and protect people (Barbier, 2006). During the 2007 Solomon Islands tsunami, the Great Barrier Reef reflected and refracted the tsunami wave back towards the ocean and reduced the energy of the wave (Baba et al., 2008). Despite these examples of the successes of natural mitigation, the effectiveness is dependent on the magnitude of the tsunami and the structure of the natural mitigation itself, including the shape, diameter, and biodiversity (Tanaka, 2009).

Figure 2.13: Mangrove forest in Phang-nga province of Thailand (Barbier, 2006).

2.3.1.4 Warnings

Warnings represent a change in the environment, and alert the public of a potential threat, prompting people to change their behaviour and take protective action, such as evacuation (Leonard et al., 2013; Potter et al., 2018). Warnings can be used to influence and generate appropriate responses to hazards, including prompting specific actions and raising situational risk perception (Potter et al., 2018; Lindell et al., 2015). Despite being the most relied upon method to mitigate tsunami risk, warnings only influence life safety and do not mitigate damage to infrastructure or property (Power & Leonard, 2013). For warnings to be effective, community engagement is required to educate the public on the expected responses to the warnings (Leonard et al., 2013).

Perry and Green (1982) presented a process experienced by a person once they have received a warning (Figure 2.14). Once someone has received a warning, they typically attempt to confirm the warning by gathering additional information or asking others. Then they attempt to confirm that the threat is real. For threats such as floods or hurricanes, this can be achieved by looking outside to check the natural environment. Once their belief of the threat has developed, the next step is to define the level of personal risk. This is largely based on the person's proximity to the threat or the affected area. Finally, once the threat has been confirmed and the person believes they are at risk, protective action can occur. This includes evacuating. This same process can be applied to tsunami. Once a tsunami warning has been received and confirmed, people can begin to take protective action and evacuate.

Figure 2.14: Process of receiving a warning and then forming a response (Perry & Green, 1982).

The way people understand, hear, believe, and confirm warnings is influential in how they respond. Studies focusing on how people react to warnings during flood, hurricane, and tornado events, show that factors such as demographic characteristics, culture, and previous disaster experience are influential in how people react to warnings, and often will encourage a positive response to the warning (Fraser et al., 2016; Potter et al., 2018; Silver, 2015). Contrary to this, false alarms or warnings disseminated for small scale events often lead to a lower perception of the risk and result in a negative response to future warnings (Tobin et al., 2013). This was observed in Japan during the 2011 Tōhoku tsunami when major tsunami warnings were released. Here, previous major tsunami warnings that had been false led to a lack of belief and complacency in the warnings and the need to evacuate in 2011 (Fraser et al., 2012).

There are three main types of tsunami warnings which are; *official, informal,* and *natural.*

2.3.1.4.1 Official Warnings

Official warnings are organised messages that are communicated from authorities through official channels such as radio, television, or emergency mobile alerts (Fraser, 2014; Leonard et al., 2013; MCDEM, 2018a). Official warnings are informed by technological warning systems including the Pacific Tsunami Warning Center (PTWC) and the Japan Meteorological Agency (JMA). The PTWC monitors seismic activity in the Pacific Ocean to inform tsunami warning decisions, while the JMA earthquake warning system detects seismic activity and provides estimated wave heights to inform tsunami warnings to the Japanese population (Fraser, 2014; Fraser et al., 2012).

The JMA issued tsunami warnings three minutes after the earthquake shaking during the 2011 Tōhoku tsunami. The warning provided estimations of a six meter tsunami wave height and advised those in coastal areas to evacuate. While the wave height warnings were much smaller than the actual tsunami heights, the warning in combination with recognition of the strong ground shaking saved many lives (Satake, 2014). The wave heights were upgraded following the detection of a large tsunami on wave gauges (Satake, 2014). While this update was disseminated prior to the arrival of the waves, power failures meant that the message did not reach many evacuees (Satake, 2014). It has been recognized that the warning system in Japan has led to an expectation of official warnings to provide information regarding the tsunami risk and instructions, and that waiting to receive official information likely delayed people's evacuations during the 2011 event (Fraser et al., 2012).

Tsunami sirens are a type of official warning that warn the public of an imminent tsunami threat and the need to evacuate. They are present in many coastal communities around the world (Fraser, 2014). Sirens are useful for distant source tsunami, where there is time to assess and confirm the tsunami threat and then formulate the message and activate the sirens, however, they are less effective in local source tsunami when there are more time constraints (Fraser, 2014). Despite tsunami sirens warning populations about an impeding tsunami threat, they are problematic in that there becomes a sense of reliance by the public on the activation of the sirens to confirm the threat (Hall et al., 2017).

2.3.1.4.2 Informal Warnings

Informal warnings are communicated in an unofficial manner from sources such as community members, friends, family, or social media, and are disseminated through unofficial channels (Fraser, 2014; Jumadi et al., 2018; Leonard et al., 2013). Informal warnings were used during the 2011 Tōhoku tsunami. Successful examples include hotel owners in Kamaishi instructing guests to higher ground, business owners in Ōfunato warning employees to evacuate, and a teacher in Ishinomaki using the school announcement system to warn the area around the school of the need to evacuate due to a large tsunami. In other areas of Japan informal warnings from the media were unsuccessful in warning people to evacuate due to power outages (Fraser et al., 2012). In the 2018 Sulawesi tsunami, an electricity blackout resulted in there being no official warnings released (Harnantyari et al., 2020). A survey on evacuation behaviour for respondents of Donggala Regency and Palu City (in Sulawesi) found that evacuees instead utilized informal warnings with information about the risk coming from face-to-face communication with neighbours and family members, and forming an evacuation decision from observing others evacuate (Harnantyari et al., 2020). Social media has enhanced the effectiveness of informal warnings, in particular, by increasing the dissemination of official warnings. This was reported in Indonesia during the 2011 Tōhoku earthquake tsunami in which official warnings were retweeted to an estimated four million people just 10 minutes after the release of an official warning (Chatfield et al., 2013).

2.3.1.4.3 Natural Warnings

Natural warnings are environmental cues that act as precursory events to a tsunami. This includes long and/or strong earthquake shaking or unusual behaviour from the ocean such as the water rapidly receding in or out of the coastline (Couling, 2014; Fraser et al., 2013; Gregg et al., 2007; MCDEM, 2018a; Power & Leonard, 2013). Natural warnings are a globally recognised strategy in reducing risk from local tsunami to coastal populations, where waves may arrive shortly after the earthquake shaking (Fraser, 2014; National Research Council, 2011). As tsunami are a complex phenomenon, the natural warnings that coastal populations may receive can differ based on the environment (Gregg et al., 2007). Furthermore, during a tsunami event not all natural warnings may necessarily be recognized by a population (Gregg et al., 2007).

The importance of identifying natural warnings has been recognised in many recent global tsunami events. This includes the 2009 Solomon Islands tsunami, where although the tsunami waves arrived three minutes after ground shaking, recognition of the natural warnings prompted people to self-evacuate, saving many lives (McAdoo et al., 2009). In Japan, while official tsunami warnings exist, previous earthquake and tsunami experience, education and storytelling has increased recognition of natural tsunami warnings (Fraser et al., 2012). In the 2018 Sulawesi tsunami, residents of Donggala Regency and Palu City reported observing environmental factors that warned them of the tsunami risk. This included noticing unusual behaviour of the sea surface, loud sounds from the ocean and observing the seawater approach the land (Harnantyari et al., 2020).

Global research on tsunami warnings shows that while people recognize natural tsunami warnings, there is a reliance and expectation on receiving official warnings (Blake et al., 2018; Couling, 2014; Currie et al., 2013; Fraser et al., 2013; Fraser et al., 2012; Fraser et al., 2016; Gregg et al., 2007; Hall et al., 2017). This applies not only for distant source tsunami, but also for local source tsunami. Despite this, communities where culture includes oral history, story-telling, tsunami education, as well as previous tsunami and earthquake experience, can lead to high recognition of natural warnings, as observed during the 2011 Tōhoku earthquake tsunami (Fraser et al., 2012). This highlights the importance of using knowledge and culture to link earthquake shaking to tsunami risk to encourage positive evacuation behaviour (Makinoshima et al., 2020)

2.3.1.5 Education

Education assists the public in understanding their tsunami risk and informs them on how to make appropriate decisions to reduce their vulnerability to tsunami (Fraser, 2014; Løvholt et al., 2014; National Research Council, 2011). Education can be targeted to improve the public's understanding on interpreting the different types of warnings, how and where to evacuate, and improve awareness of the potential impacts of tsunami and how people can undertake their own preparedness actions at home (Fraser et al., 2013; Koh et al., 2011). Education programs can take many forms, including social media campaigns, maps, television or radio campaigns, school education, public workshops, billboards, brochures (Figure 2.15), and evacuation drills (Bird & Dominey-Howes, 2008; Fraser et al., 2013; Johnston et al., 2013; Løvholt et al., 2014). Some countries also have their own disaster awareness days or months, including American Samoa who have designated September as "Disaster Awareness Month" (Dominey-Howes, & Goff, 2013). The aim of this is to promote awareness activities to produce positive responses in future tsunami (Dominey-Howes, & Goff, 2013).

Figure 2.15: Example of a brochure educating people about tsunami warnings and how to be safe during a tsunami (NOAA Weather, n.d.).

Education is an important tool in tsunami risk management as it helps to improve risk perception towards tsunami and is influential in the decisions people make before and during a response. Education programs can be targeted with messages and activities to improve risk perception or to try and influence a particular behaviour, reaction or attitude in the public (Johnston et al., 2013). This includes preparing an emergency kit or self-evacuating after natural warnings. Education can also help to improve the general public's trust in the tsunami risk strategies that have been implemented, as people are enabled to have a better understanding of how the strategies work and how they reduce their tsunami risk (Bird & Dominey-Howes, 2008).

2.3.1.6 Evacuation

Evacuation is the temporary or permanent relocation of people from a hazardous area to a safer one (Jumadi et al., 2018; MCDEM, 2016; Tobin et al., 2013; Thompson et al., 2017). This limits exposure to the threat, thereby minimizing the risk of injury and death. Evacuation is the preferred risk management strategy when the risk of remaining in an area is no longer deemed acceptable and it is safer to leave (MCDEM, 2016). Regardless of the time of day of an evacuation or the scale of the tsunami, evacuating exposed coastal areas during a tsunami response is the primary strategy to save lives and reduce the number of casualties (Kitamura et al., 2020). Evacuation during a tsunami event can be commenced once there has been a degree of forewarning and a tsunami risk has been identified (Bernard, 2005; Wei et al., 2017). This is typically either once the public have observed a natural warning or after the release of an official warning. The time constraint to evacuate during a tsunami depends on the origin of the tsunami – regional and distant source tsunami have a longer travel time so there is time to plan a managed evacuation, whereas local source tsunami have a shorter travel time so people are encouraged to self-evacuate (Jumadi et al., 2018).

Makinoshima et al. (2020) reviewed 30 reports and articles that assessed human behaviour during 17 tsunami events, to produce a common evacuation process shown below in Figure 2.16. They propose that the tsunami evacuation process involves three stages of notification, with the two main phases of response and evacuation movement. During the early period notification stage, it is likely that some coastal residents will conduct immediate evacuation behaviours. In the mid period notification stage, people begin to partake in pre-evacuation actions including contacting relatives and beginning evacuations. They note that the response phase of the evacuation movement can be diverse, however, identified common actions including seeking additional informal and official information to inform an evacuation decision and confirming the safety of family or other relatives. The action of seeking further official information has been recognised in a range of tsunami evacuation behaviour studies, and occurs as people attempt to confirm the tsunami threat is real prior to forming an evacuation decision (Fraser et al., 2016; Kanai & Katada, 2011; Lindell et al., 2015). Additional actions that can be taken during the response phase include helping others, gathering valuables, belongings and emergency gear and securing property (Couling, 2014; Fraser et al., 2013; Lindell et al., 2015). Finally, once the response phase has ended, the evacuation movement phase can begin. The quicker the tsunami risk is perceived and the fewer actions taken during the response phase, the longer time there is for residents to reduce their exposure and evacuate. Figure 2.16, shown below, outlines the evacuation process produced by Makinoshima et al. (2020), with an extra step of additional activity and evacuation. The authors highlight that during this step, residents interact with other evacuees at evacuation locations and return home to gather more essential items, or further relocate to safer locations.

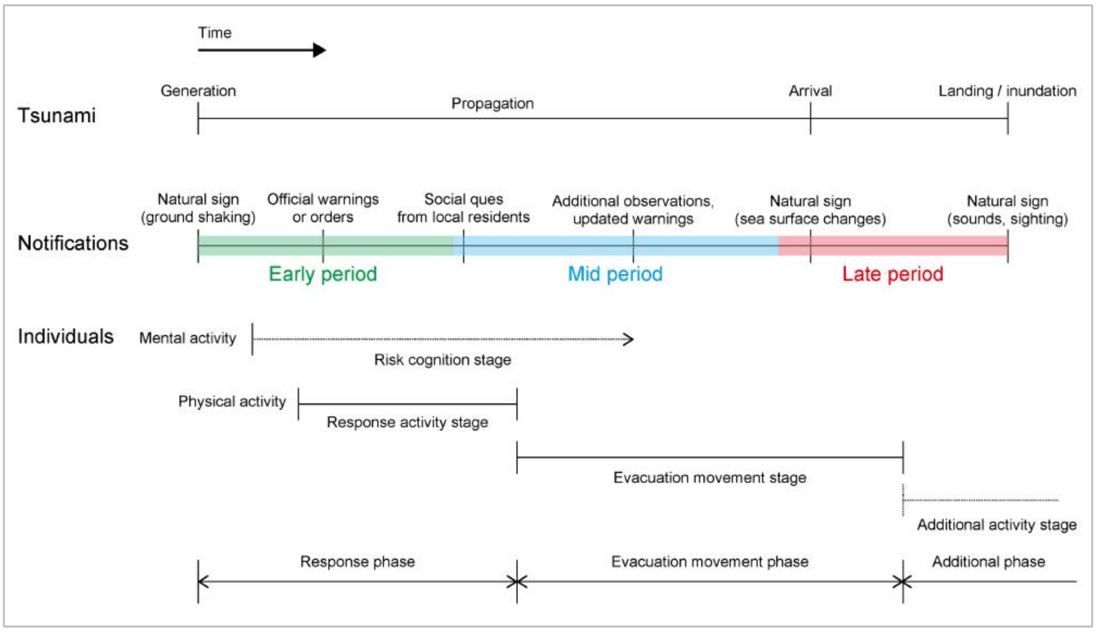

Figure 2.16: Tsunami evacuation process (Makinoshima et al., 2020).

Much of the education surrounding tsunami evacuation transport focuses on encouraging people to evacuate by walking or biking, as this means less congestion and leaves the roads open for those who cannot walk or bike to take a car – such as the elderly (MCDEM, 2016). Despite this, it has been observed that during tsunami evacuations, in areas where there is high car ownership people typically tend to drive. In Japan, where vehicle ownership is high, a high use of vehicles has been reported during tsunami evacuations (Makinoshima et al., 2017). In evacuations such as these, bottlenecks and congestion have been observed (Fraser et al., 2012; Makinoshima et al., 2017), subsequently meaning people spend more time in the exposed coastal zones. In areas where there is lower car ownership, more people are inclined to evacuate by foot. This was observed in Donggala Regency and Palu City during the 2018 Sulawesi tsunami where only 1% of those evacuated did so in a car (Harnantyari et al., 2020), and in American Samoa during the 2009 Samoa Islands tsunami where nearly 75% evacuated on foot (Apatu et al., 2016). The decision on how to evacuate is also influenced by past disaster experience, oral history, and education. In Tarō, Japan, where tsunami risk education is taught in schools and stories relating to tsunami are told, there was a positive response to the ground shaking during the 2011 Tōhoku earthquake tsunami in which people immediately began to run and evacuate towards higher ground (Fraser et al., 2012).

A substantial body of literature has been produced on evacuation behaviour for flooding, wildfires, hurricanes, volcanic eruptions, and tsunami (Brackenridge et al., 2012; Dash & Gladwin, 2007; Hasan et al., 2011; Jumadi et al., 2018; Lindell et al., 2011; Maghelal et al., 2017; Potter et al., 2018; Sun et al., 2017; Thompson et al., 2017; Toledo et al., 2018; Walch, 2018). Common themes from these works report that evacuation behaviour can be influenced by many factors including gender, living situation, age, ethnicity, previous disaster and evacuation experience, income, pets, belief and knowledge in the hazard and the warnings, preparedness actions, risk perception, transportation available, and the information being released. For example, Dash and Gladwin (2007), Thompson et al. (2017) and Toledo et al. (2018) have all found that positive evacuation behaviour is more common in females and families with children. Evacuation behaviour of elderly however, is contested with Thompson et al. (2017) reporting that evacuation is less likely in elderly populations while Toledo et al. (2018) found that the elderly are more likely to evacuate. Although households with a higher number of children have been found to be more likely to evacuate and plan for a disaster, their evacuation time is much more delayed than that of smaller households (Thompson et al., 2017). Households with pets are less likely to evacuate due to concern of a lack of pet carriers, having outdoor animals and a need to evacuate to an animal-friendly location (Thompson et al., 2017). Factors influencing negative evacuation behaviour include mobility issues, a lack of belief in the hazard (Fraser et al., 2013) a lack of transportation, and a fear of looting (Walch, 2018).

When people have experienced a false warning and unnecessarily evacuated, or have evacuated for a small event, they are likely to have low risk perception and not take protective action to evacuate (Doyle et al., 2014; Tobin et al., 2013). However, as summarised by Charnkol and Tanaboriboon (2006) and Walch (2018), when people have experienced an event previously that prompted an evacuation, it is easier for them to imagine future events and portray positive evacuation behaviour.

2.3.1.6.1 Evacuation Planning

Tsunami evacuation planning is a crucial step in the tsunami risk management process. Evacuation planning helps to ensure an efficient evacuation, with the aim of minimizing the impact on the community and those whom have been displaced (Fraser, 2014). Evacuation planning is based on knowledge of how people have reacted in previous events (Sun et al., 2017), and forms the basis of strategies to improve future evacuations. It can be achieved by individuals, or collaboratively between local or state governments, non-profit organisations and/or community members. Examples of evacuation planning include:

- **Evacuation maps** educate the public on the hazard zone and possible inundation extent. They can include key infrastructure such as assembly points and emergency services (Figure 2.17);
- **Evacuation signs** identify tsunami zone boundaries, evacuation route directions, and safe areas;
- **Evacuation exercises** allow for emergency planning to be tested. They help to improve public education of evacuation planning and tsunami risk whilst promoting knowledge of tsunami warnings and positive evacuation behaviour;
- **Vertical evacuation** involves people evacuating to tsunami resistant buildings or towers that are at elevations above the tsunami flow depth (Fraser, 2014; Kitamura et al., 2020; MCDEM, 2018a) (Figure 2.18).

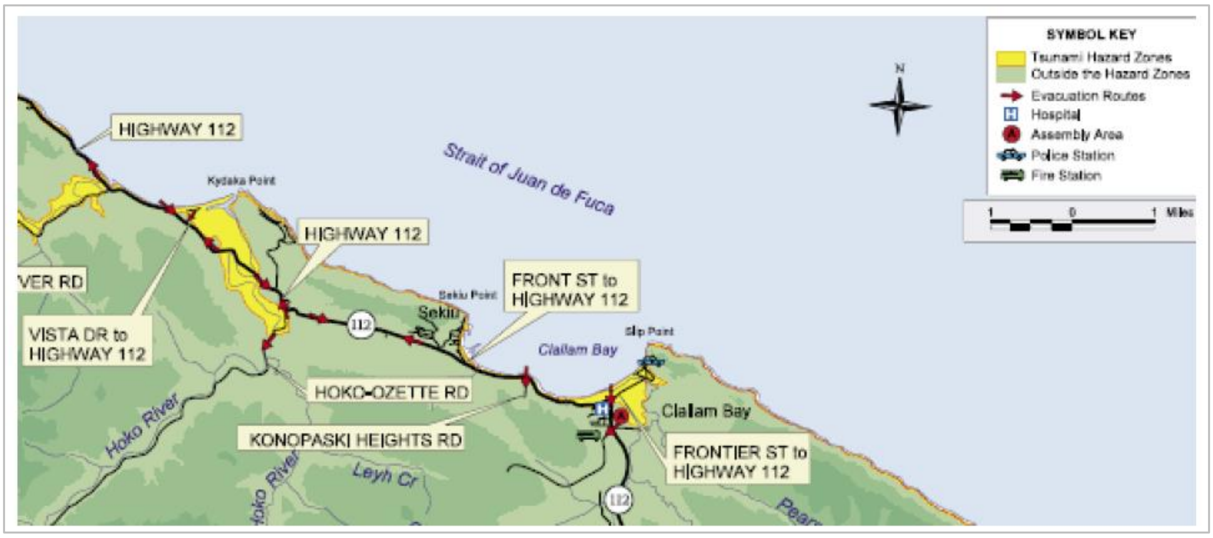

Figure 2.17: Tsunami evacuation map for Callam Bay, Washington (Fraser et al., 2012). The map shows two zones (inside the tsunami hazard zone and outside of the zone) areas of important assets, evacuation routes and assembly areas.

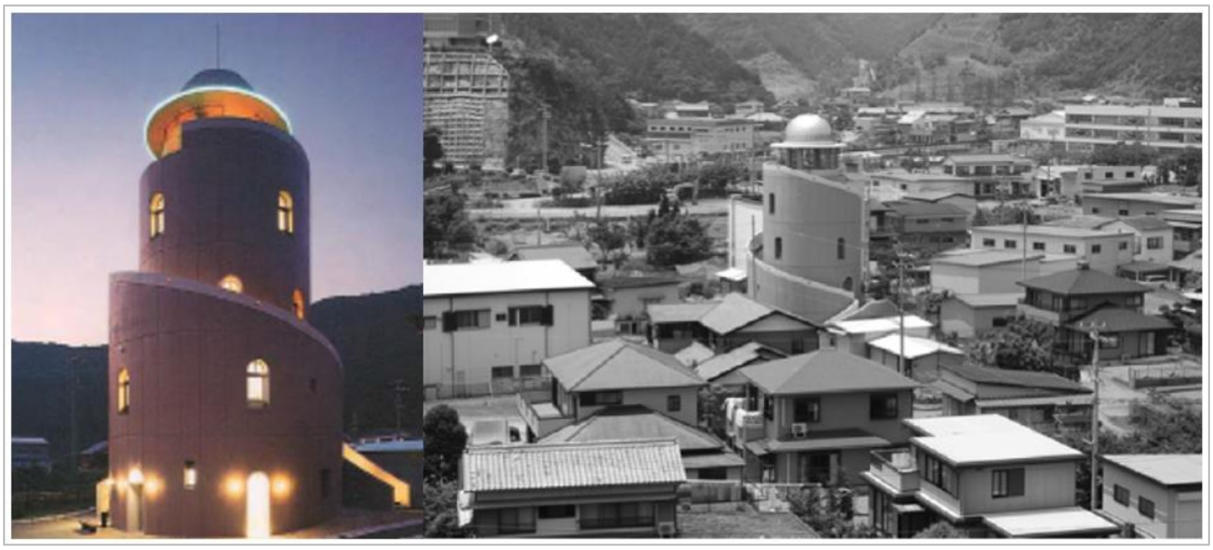

Figure 2.18: Example of a vertical evacuation structure - Nishiki Tower (Leonard et al., 2011). This tower consists of five levels and is a circular shape to reduce the lateral forces of the tsunami (Leonard et al., 2011).

2.3.1.6.2 Evacuation Exercises

Evacuation exercises allow the public to test their knowledge of tsunami evacuations and preparedness (Wafda, et al., 2013). This prompts participants to learn evacuation routes and identify safe locations (Takabatake et al., 2017), improve their confidence in the emergency planners and evacuation plans, while also learning skills to reduce injuries or fatalities during a future evacuation (Nakaya et al., 2018). Figure 2.19 shows an example of people participating in a tsunami evacuation exercise, relocating to an evacuation building. Knowledge of tsunami warnings can be integrated into evacuation exercises, aiding in improving public knowledge of self-evacuation following natural warnings, as well as informing the public on the conditions in which official tsunami warnings may be used. Evacuation exercises are useful for emergency planners as the exercises can identify issues that may occur in an evacuation, such as locations where there may be congestion or where a delay in evacuation is likely to occur (Takabatake et al., 2017). This allows for emergency plans to be refined, with the overall aim of improving the efficiency for future evacuations.

Figure 2.19: An evacuation building in Banda Aceh (Indonesia) being used in a tsunami evacuation exercise (Leonard et al., 2011).

The effectiveness of evacuation exercises in influencing positive evacuation behaviour, while a relatively un-researched topic, remains largely contested. Evacuation exercises have been reported to lead to positive evacuation behaviour in Tonga and Samoa. In these examples, the exercises assisted in educating people to self-evacuate to higher ground after experiencing earthquake shaking (Fritz, et al., 2011). In Japan during the 2011 Tōhoku earthquake tsunami, school children who had completed evacuation exercises in class were able to assess the situation and successfully evacuate uphill following the ground shaking (Fraser et al., 2012). In Japan a *"Disaster Reduction Day"* has been held annually in each prefecture. Despite this, low evacuation rates have been recorded in three locations over three separate tsunami warnings and evacuations (Fraser et al., 2012). Additionally, low participation rates during evacuation exercises have been recorded in Japan in 2005 and 2014 (Sun & Yamori, 2018). This may be that people feel the drills are monotonous or are simply not interested in participating (Kawai et al., 2015). Further issues of evacuation exercises include a lack of facilitation and discussion of evacuation route choice and behaviour from participants, as well as high organisational costs (Kawai et al., 2015; Mundai et al., 2012; Wafda et al., 2013).

2.3.1.6.3 Evacuation Modelling

To address the challenges of evacuation exercises, tsunami evacuations can be modelled. Evacuation models simulate human behaviour and represent real-life situations that may occur during an evacuation (Ronchi & Nilsson, 2016). This can provide outputs that highlight where issues may occur during evacuations, such as the time required to evacuate an area, the location of congestion and bottlenecks or estimates of the number of survivors, and casualties (Mundai et al., 2012). Similarly to evacuation exercises, evacuation modelling provides insights for emergency planners on how to improve evacuation planning to minimize the number of injuries and fatalities during future evacuations (González-Riancho et al., 2013; Mundai et al., 2012).

Evacuation modelling can be used to demonstrate and understand factors that may be influential in the evacuation process and have been used to simulate the exposure of those at risk of tsunami (including Munadi et al., 2012; Trindade et al., 2018; Wang et al., 2016; Wood & Schmidtlein, 2012; Wood & Schmidtlein, 2013). Trindade et al. (2018) presented evacuation routes for a tsunami evacuation to estimate the population exposure and required travel time where the evacuation speed was controlled by the road capacity. The results of this model showed that adopting the use of vertical evacuation structures would minimize travel time and overall population exposure to a tsunami threat (Trindade et al., 2018). Munadi et al. (2012) produced an evacuation model to simulate the time required for the population of Calang City (Indonesia) to evacuate by motorcycle and walking at two speeds and highlighted areas of congestion and bottlenecks. Wood and Schmidtlein (2012) utilized a path distance model to estimate the time required for residents and visitors to walk to safety in Grays Harbor and Pacific Counties (State of Washington, USA) (Figure 2.20). The results showed substantial variation in the time available to evacuate, with some successful evacuations possible given slow walking speeds, however, unlikely in other communities due to the distance required to travel.

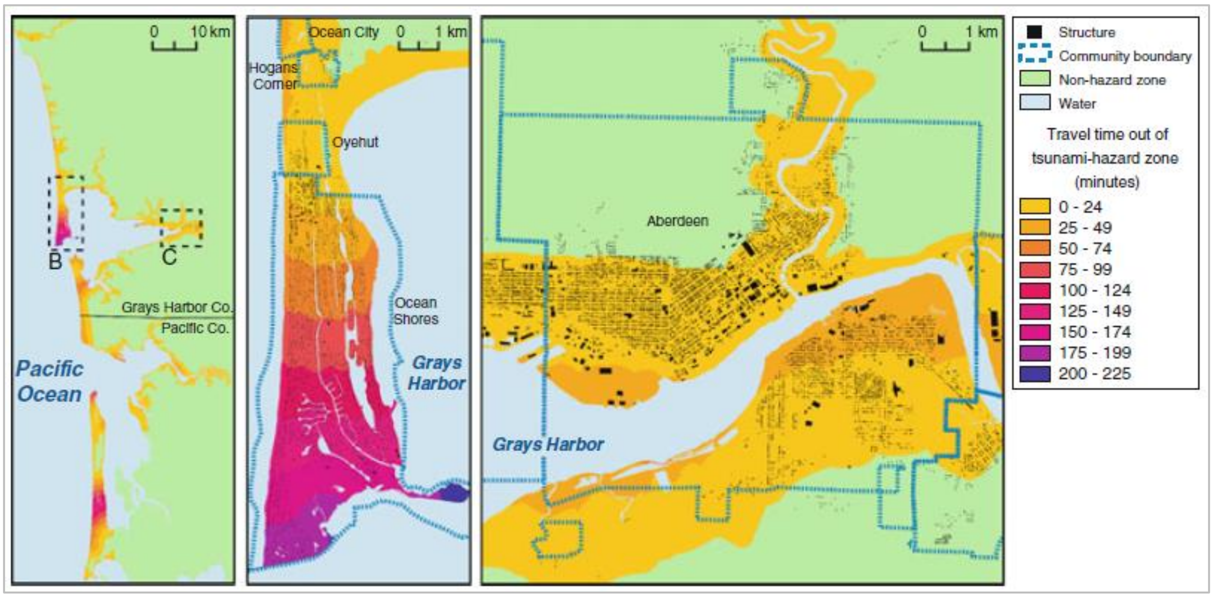

Figure 2.20: Modelled pedestrian evacuation times with a travel speed of 1.1m/s shown for the study area of Grays Harbour (a), Ocean Shores (b) and Aberdeen (c) (Wood & Schmidtlein, 2012).

Realistic evacuation models require a range of information (Lämmel et al., 2009). Typically this includes geographical information such as the road network and safe zones, hazard scenarios, and socio-economic data (Lämmel et al., 2009). Data relating to human behaviour can be incorporated into the evacuation modelling process to improve the accuracy of the modelling and is highly useful in predicting congestion and improving evacuation planning (Kubisch et al., 2019). One method of achieving this is through the integration of empirical data, such as a survey questionnaire focusing on either historical or hypothetical evacuation behaviour, into the modelling process (Kubisch et al., 2020). It has been recognised that very few tsunami evacuation models have considered the behaviour of evacuees, instead focusing on the timings of the evacuation itself (Makinoshima et al., 2016). This issue originates from the lack of observed tsunami evacuation behaviour (Makinoshima et al., 2016). Human behaviour during evacuations is complex (Wafda et al., 2013). Incorporating this data into the modelling process increases the validity of the modelling outputs by producing realistic evacuation models that better represent the population (Kubisch et al., 2019). It can also allow for the results to include multiple behaviours and actions that may occur during an evacuation, rather than focusing on the ideal evacuee behaviour of evacuating immediately to the nearest safe location (Makinoshima et al., 2016). Despite the benefits of incorporating social science into evacuation modelling, it has rarely been done, with many researchers focusing solely on the modelling or the social science (Kubisch et al., 2019; Kubisch et al., 2020).

Table 2.3 presents a comparison of three methods that can be used for tsunami evacuation modelling. The advantages and disadvantages of each are outlined, with details on the modelling type chosen for this research project presented in Section 4.

Table 2.3: Comparison of evacuation modelling methods that can be used to model tsunami evacuations.

Modelling Method	Advantages	Disadvantages
Least cost distance	• Evacuation routing is not constrained to roading network allowing for different transportation types to be considered (Harris et al., 2015). • Slope and land are integrated when calculating evacuation time (Harris et al., 2015) allowing for the evacuation model to focus on the characteristics of the landscape (Wood & Schmidtlein, 2013). • Is compatible with GIS (Harris et al., 2015). • Useful for modelling pedestrian evacuations (Le, 2016).	• Only calculates the shortest path (Harris et al., 2015). • A high resolution of data is needed to allow the model to calculate to the raster (Harris et al., 2015).
Agent based	• Simulates real life scenarios allowing the model to be close to reality (Harris et al., 2015). • Works for different transport methods (Wafda et al., 2013). • Is flexible and provides a natural description of a system (Munadi et al., 2012). • Represents individuals or groups of people (Fraser et al., 2013). • Focuses on the interactions and actions of agents (Wang et al., 2016). • Agents are given a set of characteristics and follows rules depending on their role, allowing them to assess the situation and form an evacuation decision (Dawson et al., 2011; Mas et al., 2015).	• Computationally expensive (Le, 2016). • Requires a lot of data to be input into the model (Harris et al., 2015). • Requires both detailed spatio-temporal information and information on the social dynamics and characteristics of the area of study (Yeh, 2014).
ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing)	• Three methods of modelling are available – shortest path, capacity constrained route planner and CASPER (Harris et al., 2015). • Easy to validate models and reproduce (Harris et al., 2015). • Features a flocking tool that acts as an agent based model (Trindade et al., 2018). • Is freely available (Trindade et al., 2018).	• Only works on ArcMap in the Network Analyst tool (Harris et al., 2015). • Requires an up-to-date network with no inaccuracies (Harris et al., 2015).

2.3.2 Christchurch and Banks Peninsula Tsunami Risk Management

New Zealand's tsunami risk management efforts began in the 1960's, following a tsunami that originated off the coast of Chile generated from a M_w 9.5 earthquake (Johnston et al., 2008). Although the PTWC had been established in Hawaii, New Zealand was not a member, thus the tsunami waves hit New Zealand without the release of an official warning (Johnston et al., 2008). Following this, arrangements were made for New Zealand to receive warnings from the PTWC, and in addition, wave travel time maps, and public education resources were made available in New Zealand (Johnston et al., 2008).

The 2004 Indian Ocean tsunami significantly changed how tsunami risk is managed both on a global scale and locally within New Zealand (King, 2015; MCDEM, 2016). Global improvements to tsunami risk reduction included real-time estimation of the tsunami travel time from the origin to the destination, paleo-tsunami studies to understand the risk and sources of tsunami, creation of seawalls, designated evacuation areas, and general improvements to public education (Satake, 2014). The impacts from the 2004 Indian Ocean tsunami event sparked an improvement in financial and human resources from the New Zealand Government to go towards New Zealand's tsunami risk management (Johnston et al., 2008). This saw a framework for a national tsunami risk management strategy to be created. Developments from this strategy included a probabilistic tsunami hazard assessment, tsunami signage standards, evacuation zone guidelines, development of a warning system, tsunami response planning, and an increased awareness of tsunami risks (Fraser et al., 2016; MCDEM, 2016).

The 2011 Tōhoku tsunami further emphasised the importance of effective tsunami risk management, prompting additional developments in probabilistic tsunami modelling, understanding of tsunami science, and warning and evacuation practices (MCDEM, 2016).

The remainder of this section details the tsunami risk management strategies that have been implemented in Christchurch and Banks Peninsula.

2.3.2.1 Warnings

The National Emergency Management Agency (NEMA) promotes official, informal, and natural warnings as the primary warning sources for communicating tsunami risk in New Zealand (Leonard et al., 2011; MCDEM, 2016). The type of warning that is issued is dependent on the origin of the tsunami and the travel time from the source to the destination.

2.3.2.1.1 Official Warnings

Official warnings are used to inform the public of a distant or regional tsunami threat. Official tsunami warnings are issued by NEMA and are founded on information received from the PTWC, who issue tsunami notifications based on the size and locations of earthquakes, and from GNS Science/GeoNet, who monitor and detect local tsunamigenic earthquakes on and off shore the New Zealand coast (MCDEM, 2018a).

Official warnings regarding tsunami threats are disseminated by NEMA to local Civil Defence and Emergency Management (CDEM) Groups and news media through the National Warning System (NWS) to then reach communities (MCDEM, 2017a) (Figure 2.21). The message that is released is dependent on the threat and the known information (Figure 2.22). Once a local CDEM Group has received a warning through the NWS, they can coordinate a local response for their affected communities. There is a Memorandum of Understanding (MOU) between NEMA and key media broadcasters to disseminate tsunami warnings through national radio and television to achieve a higher level of awareness of a threat from coastal communities (MCDEM, 2017a). Official warnings can be disseminated through multiple platforms, including social media channels, websites, television, radio, phone calls, door knocking, emergency mobile alerts, and sirens (Fraser, 2014; MCDEM, 2018a).

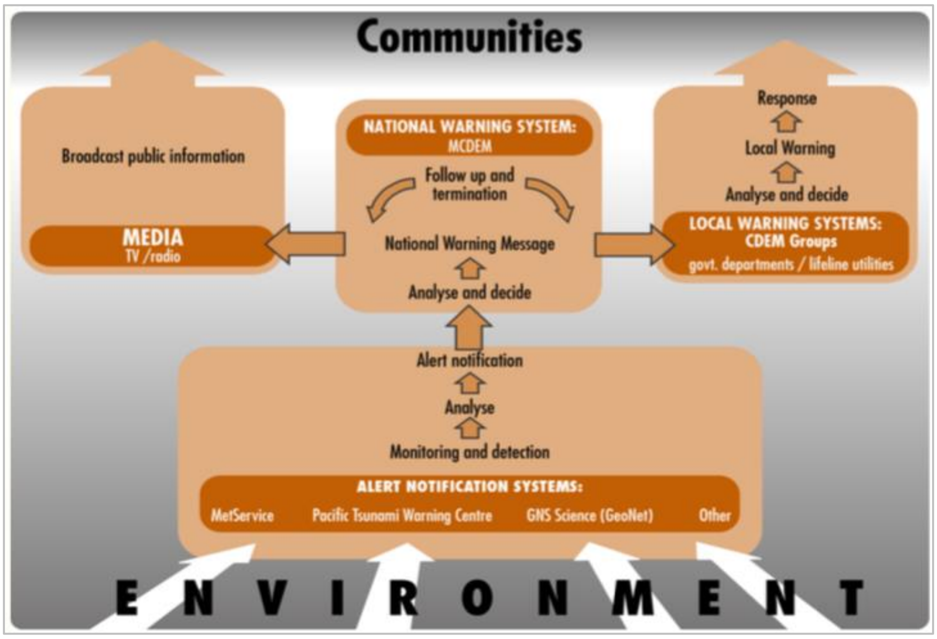

Figure 2.21: The National Warning System (NWS). This is used to disseminate alerts up to local CDEM Groups who can then warn their communities and activate local warnings, and to media who broadcast the alert to the general New Zealand public (MCDEM, 2017a) Note that this figure was produced prior to the establishment of NEMA, thus MCDEM represents NEMA's role in the NWS.

National Advisories:

- *National Advisory – No Tsunami Threat to New Zealand*
- *National Advisory – Earthquake Being Assessed*
- *National Advisory – Large Pacific Earthquake Being Assessed*
- *National Advisory – Earthquake – No Tsunami Threat to New Zealand*

National Warnings:

- *National Warning – Tsunami Threat – Local source*
- *National Warning – Tsunami Threat to Beach and Marine Areas*
- *National Warning – Tsunami Threat to Land and Marine Areas*

Tsunami cancellation messages:

- *National Warning – Tsunami Threat CANCELLED*

Requests for broadcast, or termination of broadcast:

- *Request for the broadcast of a Tsunami Threat*
- *Request for the termination of an emergency announcement*

Emergency Mobile Alerts:

- See Section 6

Figure 2.22: Types of official notification that NEMA may issue for a potential tsunami threat or following a large earthquake (MCDEM, 2018a). These notifications are issued through the NWS to those on the NWS Register. The warning issued is dependent on the tsunami threat and the information known at the time.

Although official warnings are typically used for distant and regional source tsunami, when a local tsunami source has been detected, NEMA will issue warning messages via the NWS (MCDEM, 2017b). This helps to reinforce the tsunami risk and encourage those in coastal locations to evacuate. While the warning may be issued after the first waves have arrived, the waves may travel to other locations around the New Zealand coast, thus the warnings may still be valuable (MCDEM, 2018a).

Tsunami sirens are a type of official tsunami warning. The use of tsunami sirens falls under the responsibility of local CDEM Groups (MCDEM, 2014). Many urban areas around New Zealand have tsunami sirens, with Christchurch having 45 along its coastline (Kardos, 2017; Fraser, 2014). Figure 2.23 shows the location of tsunami sirens in Sumner, Christchurch. Tsunami sirens may be activated for distant source tsunami threats, and where possible regional threats, but must not be an expected alerting system by the public for local source tsunami (MCDEM, 2014). Despite this, it has been recognised that there is a reliance by the public on the activation of tsunami sirens to prompt evacuations during tsunami events (Fraser et al., 2013). This emphasizes the importance of tsunami education to enable the public to correctly interpret tsunami warnings and decrease their risk. One way that this is achieved is by combining the promotion of the correct interpretation and use of the tsunami sirens with the testing of the tsunami sirens, which occurs bi-annually (MCDEM, 2014).

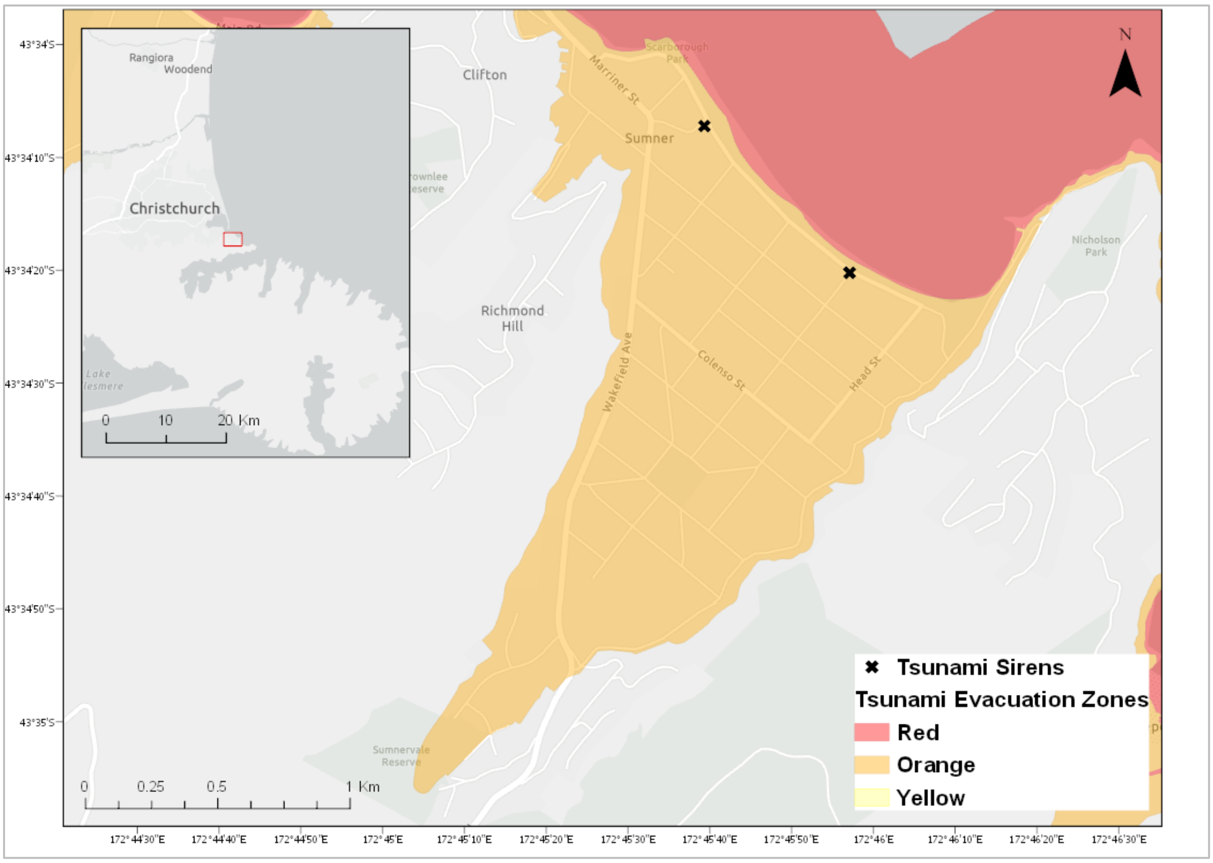

Figure 2.23: Location of two tsunami sirens in Sumner, Christchurch.

2.3.2.1.2 Informal Warnings

Informal warnings are a recognised tsunami warning source for the New Zealand public. Informal warnings can be received through local or international media coverage following the release of a tsunami warning/watch by the PTWC, or from people who have either experienced a natural cue or have heard official broadcasts (Tsunami Working Group Signage Committee & GNS Science, 2007).

2.3.2.1.3 Natural Warnings

Natural warnings are the primary warning for local source tsunami (MCDEM, 2017a). Given the proximity of local source tsunami to the coastline and the short travel time of these tsunami, it is unlikely that there will be sufficient time to implement an official warning (Couling, 2014; Kardos, 2017; MCDEM, 2017a). For this reason, it is advised by NEMA that if the public observe a natural warning, they should evacuate immediately from all coastal zones (Blake et al., 2018; MCDEM, 2016; MCDEM, 2018a).

“If an earthquake is long or strong: get gone. Move immediately to the nearest high ground or as far inland as possible. Don’t wait for an official tsunami warning” (MCDEM, n.d.).

Natural warnings are also a recognized warning for regional source tsunami in which long duration earthquake shaking may be felt.

Blake et al. (2018), Couling (2014) and Fraser et al. (2016) have researched the use and interpretation of tsunami warnings in communities around New Zealand. Common themes from these pieces include a reliance on official warnings from Civil Defence through mediums such as television, radio, and social media, (Blake et al., 2018) and through tsunami sirens (Couling, 2014; Fraser et al., 2016). The infrequency of tsunami events and the lack of tsunami evacuations in Canterbury means that there is little information on how the public responds to tsunami warnings and how this may relate to evacuations.

2.3.2.2 Education

Tsunami education in New Zealand aims to increase public awareness of tsunami and improve readiness towards future events (Fraser et al., 2013; MCDEM, 2017a). In New Zealand, tsunami education initiatives are led by NEMA through the National Public Education Program. This consists of a national media campaign and school programs, as well as additional activities that are completed by NEMA – to support the programs – and by CDEM groups –to build on the programs at a community level (MCDEM, 2017a). A multi-media approach is utilized to ensure the messages have a wide reach (MCDEM, 2017a).

At a national level, strategies include media advertising through television, radio, newspapers, in the "Yellow Pages" phonebooks, the *'Get Ready, Get Thru'* website to promote readiness (Get Ready, n.d.), school resources (NEMA, n.d.d), social media campaigns, brochures promoting hazards and preparedness methods, the '*Long and Strong, Get Gone'* campaign, and a national shakeout exercise (NEMA, n.d.c) (Fraser et al., 2013; Johnston et al., 2013).

Although not specifically a part of NEMA's Public Education Program, tsunami sirens are tested as part of a twice-yearly exercise at the change of daylight savings time, helping promote tsunami risk awareness and education on tsunami warnings (MCDEM, 2014).

Following the 2010-2011 Canterbury earthquakes, CDEM held public meetings to discuss tsunami risk with many of the coastal communities of Christchurch (Schoenfeld, 2018). CDEM has also directly worked with coastal communities around Christchurch and Banks Peninsula to improve awareness and preparedness towards tsunami risk (Schoenfeld, 2018). Both Canterbury Civil Defence and Emergency Management (Canterbury CDEM) and Christchurch City Council Civil Defence and Emergency Management (CCC CDEM) have information regarding tsunami risk and reduction strategies available on their websites for the public (CCC, n.d.b; Canterbury CDEM, n.d.).

Education on tsunami awareness has also been initiated at a community level in Christchurch. The New Brighton Project offers new community members a welcome pack, which includes a Civil Defence brochure which explains the types of tsunami warnings and how to react to them (E. Addock, personal communication, Nov 21, 2018). Schools in Sumner and Redcliffs have completed tsunami evacuation drills. In these exercises, in an effort to raise awareness amongst students and their families of how to react to a tsunami threat when long or strong earthquake shaking is observed, children and their teachers walk to higher ground (Redcliffs School, 2016; Sumner School, n.d.).

2.3.2.3 Evacuation

Evacuation is the primary risk management strategy once a tsunami been identified and it is no longer safe for people to remain in coastal locations (Jumadi et al., 2018; MCDEM, 2016; Tobin et al., 2013; Thompson et al., 2017).

Tsunami evacuation planning in New Zealand is nationally consistent, and is framed around evacuation zones, evacuation signage, maps, and response actions, and complimented by evacuation routes (MCDEM, 2008; MCDEM, 2016). In Christchurch and Banks Peninsula, evacuation planning has been undertaken by CCC CDEM with guidance from Canterbury CDEM and NEMA. The primary evacuation planning strategies that have been implemented in Christchurch and Banks Peninsula are evacuation zones and routes.

Tsunami evacuation zones in Christchurch and Banks Peninsula have been informed by distant, regional, and local source tsunami inundation modelling (Jack, 2019; Jack & Schoenfeld, 2017; Kohout et al., 2015; Lane et al., 2014; Lane, Kohout, et al., 2017; Mueller et al., 2019). Evacuation zones are areas that authorities advise people to evacuate from after the recognition of a natural warning or after receiving an official warning (Jack & Schoenfeld, 2017) (Figure 2.24). They are not hazard or inundation zones (Jack & Schoenfeld, 2017), but instead represent a combination of various inundation scenarios developed from modelling different tsunami scenarios (Jack, 2019). Evacuation zones assist in communicating tsunami risk to the public and in the response undertaken by authorities during a tsunami evacuation (Jack & Schoenfeld, 2017; MCDEM, 2016). As new modelling techniques are available, and tsunami inundation scenarios become more accurate, evacuation zones for Christchurch and Banks Peninsula have been updated to reflect these changes. For example, evacuation zones were improved in 2017 for both Banks Peninsula and Christchurch (Jack & Schoenfeld, 2017). In 2019 these zones were further improved for Christchurch to reflect advances in modelling that cover worst-case inundation from large tsunami (Jack, 2019). Evacuation zones are available online for residents to access (Canterbury Maps, n.d.; CCC, n.d.b; ECan, n.d.).

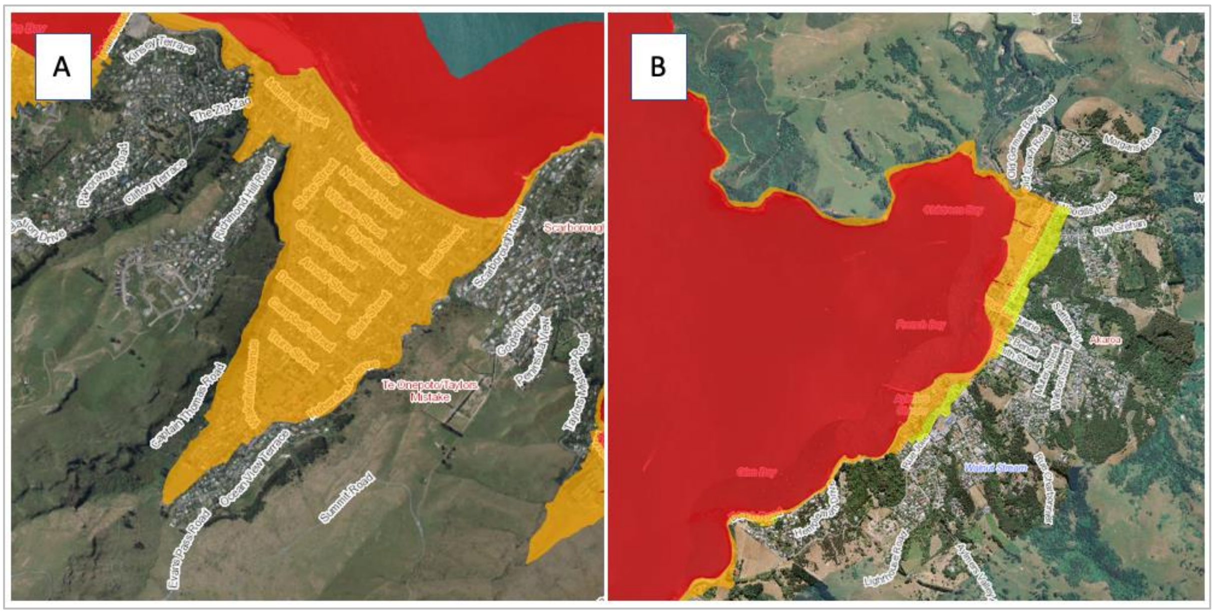

Figure 2.24: Tsunami evacuation zones for Sumner, Christchurch (A) and Akaroa, Banks Peninsula (B) (ECan, n.d.).

Consistent with the national standards for evacuation zones, three evacuation zones have been utilized in Christchurch and Banks Peninsula. These are the yellow, orange, and red zones. The use of the three zones was chosen by NEMA to reflect a range of tsunami risk scenarios, with the hope that there will not be evacuations that are larger than what is necessary, as this can be difficult to manage and can result in a lack of trust in authorities (MCDEM, 2016). The red evacuation zone is the highest risk zone. It includes beach and marine areas, and access to these areas would be restricted during any tsunami (MCDEM, 2016). At a national level, the largest tsunami risk is a local source tsunami. Therefore, following an official warning the orange zone would be evacuated for distant and regional, while the yellow zone, which covers all maximum credible events including the worst-case scenario, would be evacuated based on natural and informal warnings for a local source tsunami risk (MCDEM, 2016). As outlined in Section 2.2.2, tsunami hazard assessments reveal that in terms of wave height and extent of inundation, the worst case scenario and biggest tsunami risk for Christchurch and Banks Peninsula is a distant source tsunami (Jack, 2019). This is followed by a regional source tsunami and then a local source event (Jack, 2019). For this reason, CDEM recommends that people in Christchurch and Banks Peninsula should evacuate the red and orange zones after feeling long or strong earthquake shaking, while should evacuate all three zones (red, orange, and yellow) following instructions in an official warning (Jack, 2019; Jack & Schoenfeld, 2017).

Evacuation routes provide information for the population on how to quickly and safely escape from hazardous areas to safer ones (Yamamoto & Li, 2017). Christchurch City Council (CCC) have developed suggested evacuation routes for coastal communities of Christchurch that are available online (CCC, n.d.b). Examples of these can be viewed in Figure 2.25.

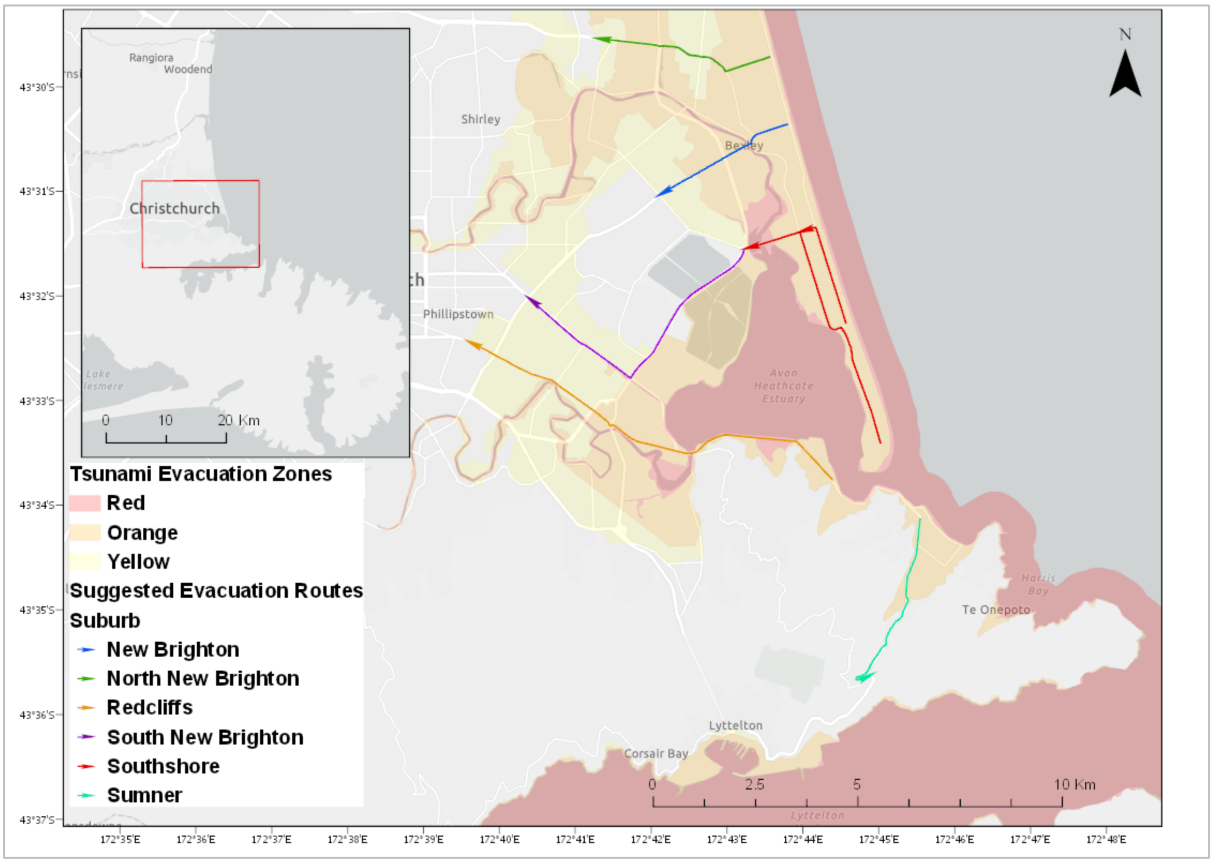

Figure 2.25: Primary tsunami evacuation routes suggested by CCC (adapted from CCC, n.d.b).

Tsunami evacuation exercises are held yearly throughout New Zealand. The national *'ShakeOut'* exercise is organized by MCDEM and incorporates an earthquake drill with a tsunami hikoi (walk) (Get Ready, n.d.). This promotes knowledge of natural tsunami warnings and encourages positive evacuation behaviour through the importance of walking to evacuate. This event also prompts the public to plan their evacuation routes. Residents, community groups and schools throughout Banks Peninsula and Christchurch are encouraged to participate in this event.

Only a limited number of studies exist in New Zealand regarding tsunami evacuation behaviour (Blake et al., 2018; Couling, 2014; Currie et al., 2013; Fraser et al., 2013; Fraser et al., 2016). Themes from these studies include a reliance on using cars to evacuate, delayed evacuations due to gathering items such as emergency kits and checking on others, an expectation on receiving an official warning (to warn of or confirm the tsunami threat) and a low risk perception of tsunami due to the infrequency of events. Only one tsunami evacuation behaviour and knowledge study specific to Banks Peninsula and Christchurch has been conducted. This study surveyed residents and visitors in 11 suburbs of Christchurch and Banks Peninsula to determine changes in knowledge of perception of tsunami risk, as well as compare the differences between the tsunami knowledge of residents and visitors (DuBois, 2007). This study found that while residents had a high level of awareness and risk perception towards tsunami, they had low levels of preparedness activities (DuBois, 2007). While the 2004 Indian Ocean tsunami had contributed to awareness and knowledge of tsunami, there was a lower level of awareness about general tsunami information amongst visitors compared to that of residents (DuBois, 2007).

2.3.2.3.1 Evacuation Modelling

Although the use of tsunami evacuation modelling within New Zealand has been limited, there are some examples explaining the development and use of various methods of evacuation modelling (Fraser et al., 2014; Knook et al., 2015; Le, 2016; Tilley, 2018; Power et al., 2019). Evacuation modelling has also been completed for Christchurch. Le (2016) presented a spatio-temporal distribution of different population groups to reflect diurnal and seasonal population variation. This provided a more realistic assessment of the exposure of the Sumner population to inform a least cost path distance evacuation model for private vehicle and pedestrian evacuation during a distant source tsunami (Le, 2016). An example of the results by Le (2016) can be viewed in Figure 2.26. This allowed for different evacuation zones around Sumner to be identified along with optimal evacuation paths. Tilley (2018) developed a vehicular evacuation model for New Brighton, South Brighton, and Southshore. The results of this model, shown in Figure 2.27 revealed that a proportion of the population would take more than 100 minutes to evacuate and that particular road segments would experience significant traffic flows resulting in congestion (Tilley, 2018). As a part of the *'Quicker, Safer Tsunami Evacuations'* research, agent based tsunami evacuation models have been developed for Sumner (Power et al., 2019). Evacuation models have also been developed for Napier and Petone through this national evacuation modelling project. For each area, including Sumner, a workshop was held to allow community members to critique the models and identify evacuation routes that were not in the model (such as through parks or hidden walking tracks) or evacuation routes that were in the model but are not available in reality (Power et al., 2019). This allowed for improvements to be made to the models so that they better represented the communities. A further workshop/meeting was held to present the results of the modelling back to the community (Power et al., 2019). This workshop coincided with the release of updated tsunami evacuation zones for Sumner, and allowed authorities the opportunity to explain the changes of the zones and what this means for future evacuations. A lack of documented tsunami evacuation behaviour in Christchurch and Banks Peninsula has meant that that evacuation modeling has yet to be completed for these communities that incorporates real-life behaviour.

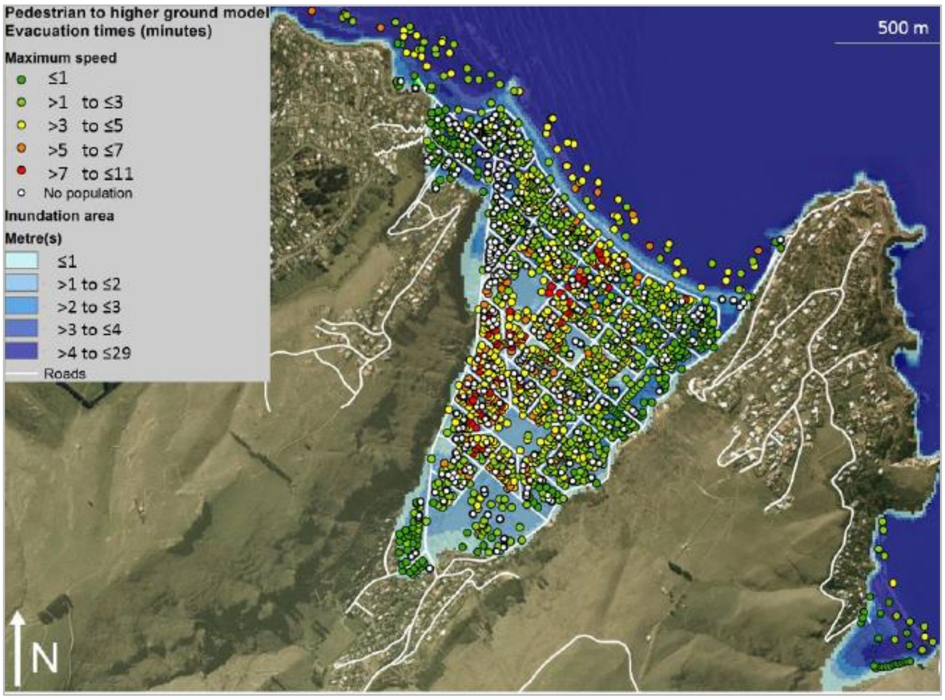

Figure 2.26: Evacuation time for Sumner in a February weekend 12:00 scenario showing the maximum evacuation speed for pedestrians (Le, 2016).

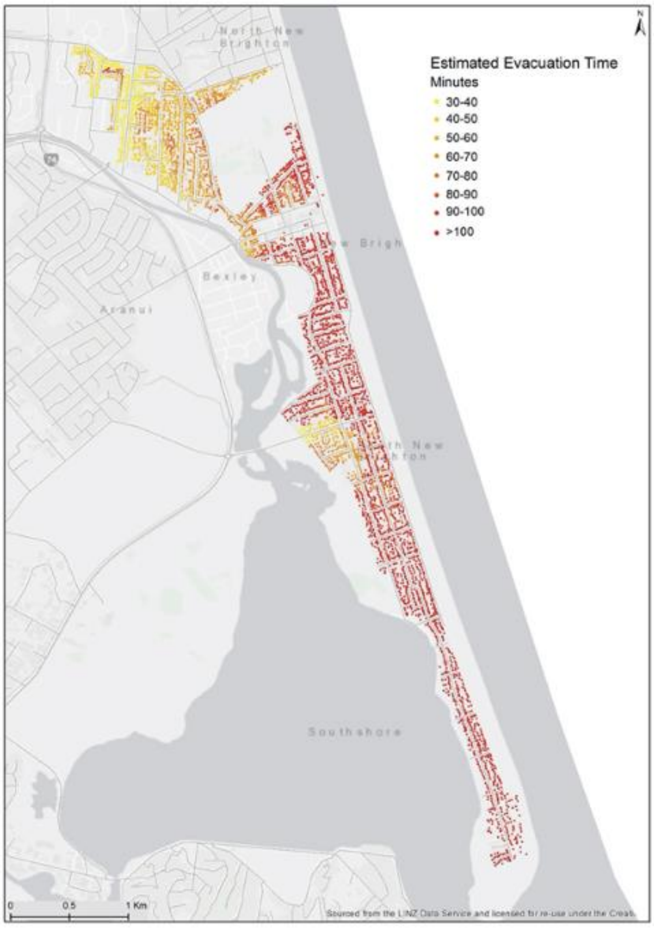

Figure 2.27: Estimated evacuation time for New Brighton, South Brighton and Southshore to evacuate for a tsunami threat by car (Tilley, 2018).

2.4 CASE STUDY: THE KAIKŌURA EARTHQUAKE

This section provides an outline on the 2016 Kaikōura earthquake, the tsunami generated from this earthquake and an overview of the tsunami response by authorities and Christchurch and Banks Peninsula residents. This case study illustrates the need to better understand reactions to tsunami warnings, tsunami evacuation behaviour and preparedness.

At 12:02 a.m. (NZDT) on November 14 2016, a M_w 7.8 earthquake ruptured near Kaikōura causing considerable damage to homes, infrastructure and the natural environment, as well as interrupting the economic sector of New Zealand (MCDEM, 2017b; Power et al., 2017) (Figure 2.28). The earthquake shaking lasted almost 2 minutes and was felt widely throughout New Zealand (Blake et al., 2018; Wotherspoon et al., 2017). Reports indicated shaking intensities of strong, severe or extreme being felt by those between Christchurch and Wellington (Lane et al., 2020), as can be seen in Figure 2.29 and Figure 2.30.

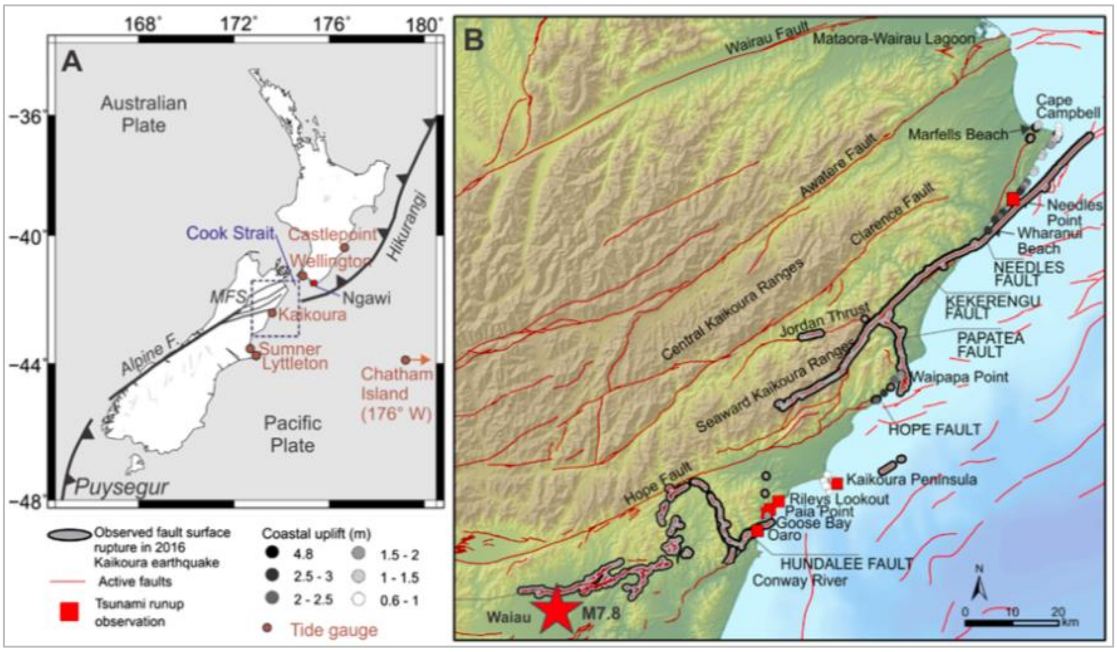

Figure 2.28: Tectonic setting of the 2016 Kaikōura earthquake (Power et al., 2017). Image B also includes tsunami run-up observations, onshore and offshore active faults in the Kaikōura/Marlborough region, and the faults that ruptured during the Kaikōura earthquake.

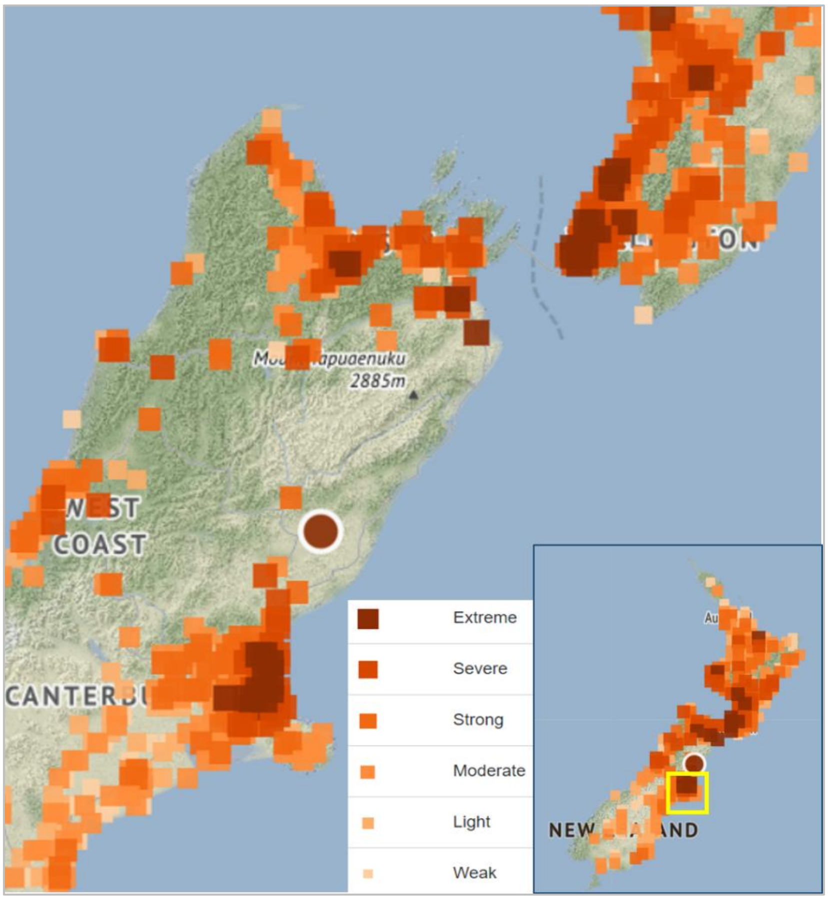

Figure 2.29: Shaking map showing the location of the 2016 Kaikōura earthquake and the reported shaking (Geonet, n.d.a)

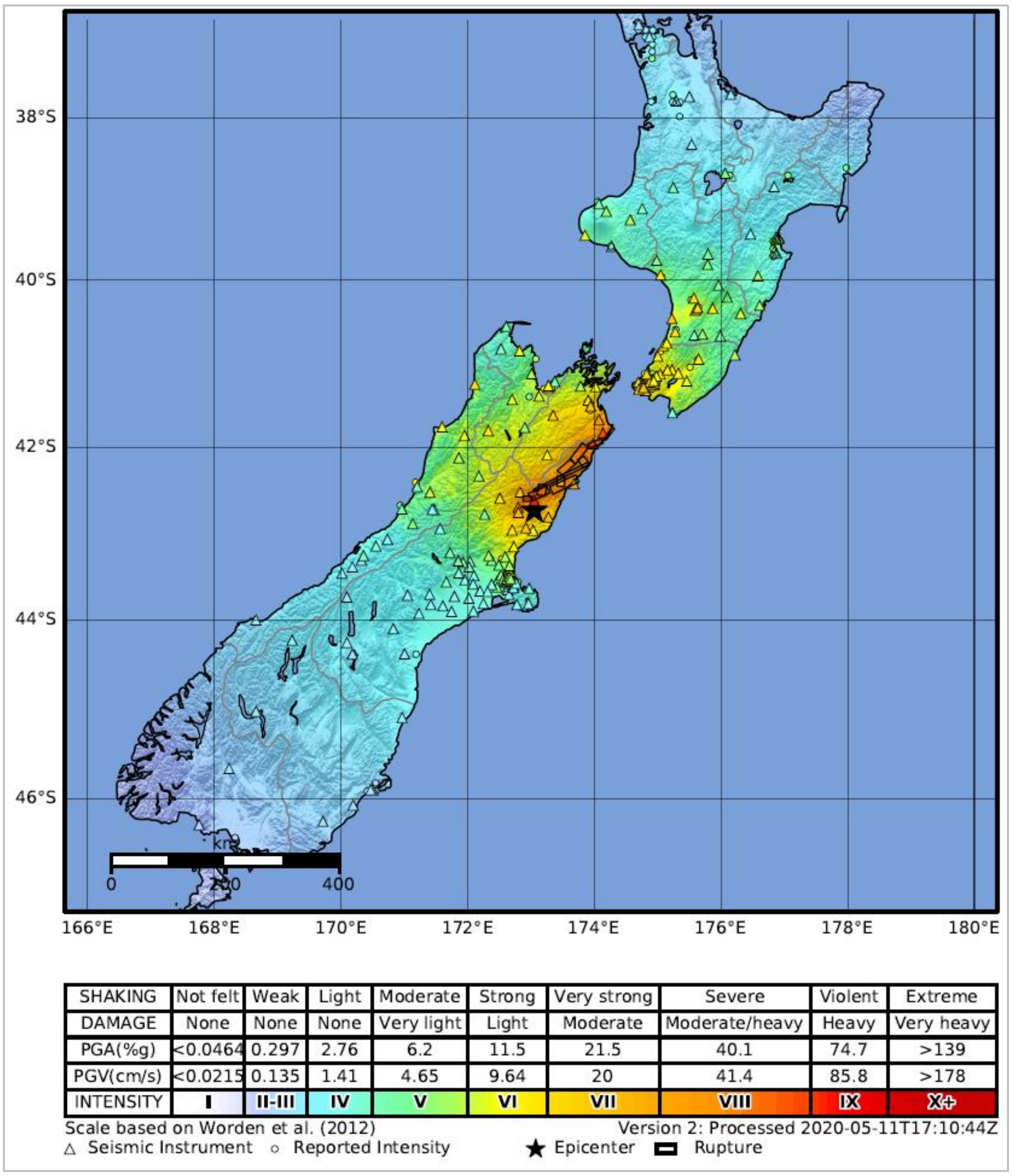

Figure 2.30: Shake map of reported shaking intensity during the 2016 Kaikōura earthquake (USGS, n.d.)

The Kaikōura earthquake was a complex event (Blake et al., 2018). The epicentre was 80 kilometers inland, and at least 21 faults ruptured, four of which were offshore (Blake et al., 2018; Power et al., 2017) (Figure 2.28). This produced the largest local source tsunami in New Zealand since 1947, with tidal gauges along the eastern coastlines of Marlborough and Canterbury recording run-up height observations between 0.9 and 6.9 meters (Power et al., 2017) (Figure 2.31; Figure 2.32). The greatest damage from this tsunami was in Little Pigeon Bay (Banks Peninsula) where a cottage was damaged (Lane, Borrero, et al., 2017) (Figure 2.33).

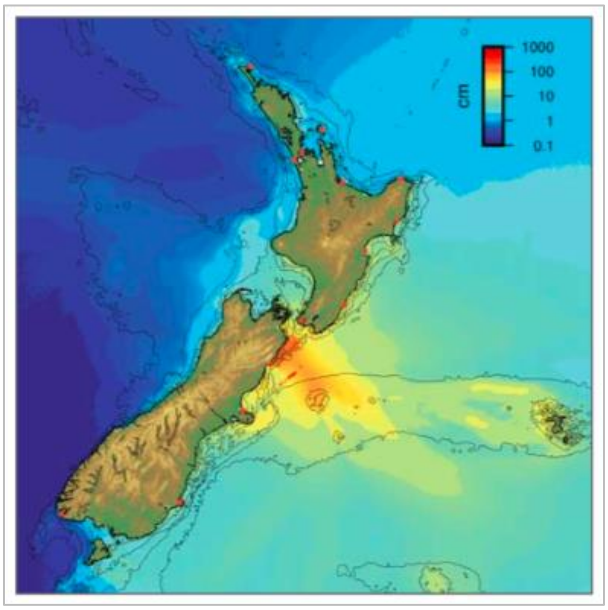

Figure 2.31: Propagation of tsunami waves generated during the Kaikōura earthquake (Borrero & Lane, 2018). The majority of the waves radiated offshore. Warmer colours indicate higher tsunami amplitudes.

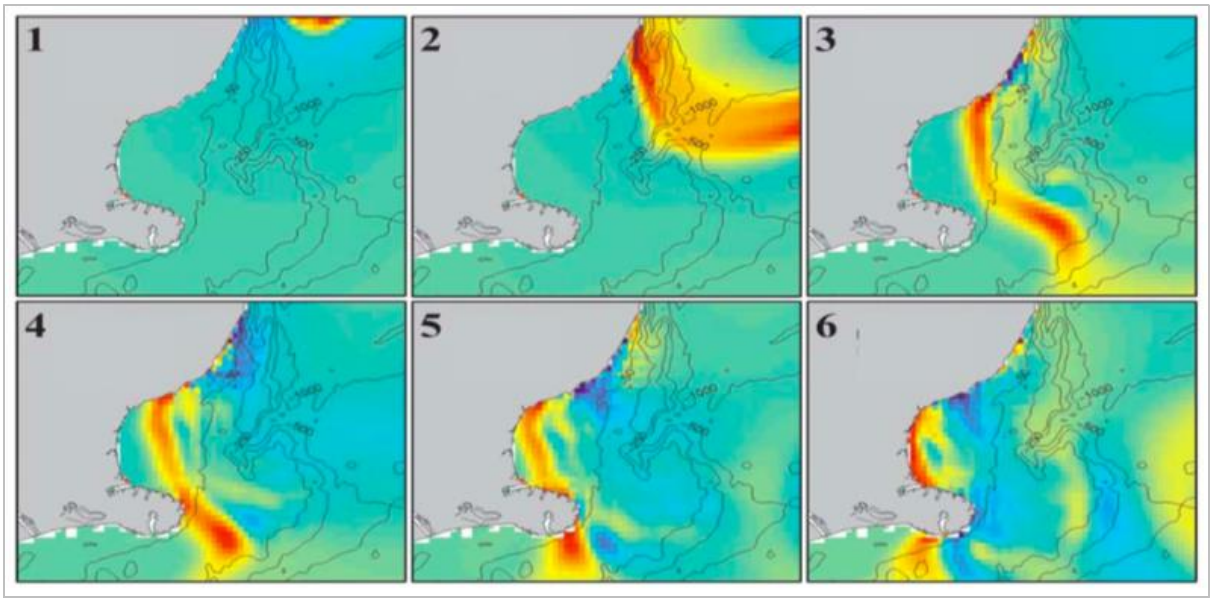

Figure 2.32: Movement of tsunami wave generated during the Kaikōura earthquake towards Banks Peninsula (Borrero & Lane, 2018). The warmer colours indicate higher tsunami amplitudes.

Figure 2.33: Damage observations for the cottage in Little Pigeon Bay that was damaged in the 2016 Kaikōura tsunami. Image A shows the damage on the outside of the house where the deck was removed and veranda poles displaced. Image B shows an internal water mark approximately 1 meter above the floor (Lane, Borrero, et al., 2017).

Following inspection of raw tidal gauge data for three gauges near Christchurch, signs of the tsunami first showed approximately 1 hour and 15 minutes after the earthquake (Lane, Borrero, et al., 2017). Maximum wave amplitudes were recorded during this event for Sumner and Lyttleton, with Sumner reaching +0.63 meters at 3:59 a.m., and Lyttleton +0.49 meters at 3:45 a.m. (Lane, Borrero, et al., 2017).

2.4.1 Response to the Kaikōura Tsunami for Christchurch and Banks Peninsula

The Kaikōura earthquake generated a regional source tsunami for Christchurch and Banks Peninsula. The response to this tsunami was multi-faceted, with many issues arising. An overview of the response is presented below, followed by a timeline of the response (Figure 2.34). Further details surrounding the response to this event are presented by Kardos (2017), Lane et al. (2020), MCDEM (2017b) and Schoenfeld (2018).

Founded on initial information regarding the epicentre and magnitude of the Kaikōura earthquake, at 12:40 a.m. MCDEM issued a national advisory stating that there was no tsunami threat to New Zealand (Kardos, 2017; MCDEM, 2017b; Power et al., 2017). Although some people in coastal communities of Christchurch and Banks Peninsula self-evacuated following the natural warning of the earthquake shaking, it was recognised by CCC CDEM that many did not (Kardos, 2017).

At 1:00 a.m., following the observation of a 2.5 meter sea level drop in Kaikōura, a tsunami threat was issued by MCDEM for all southern coastal areas of New Zealand (MCDEM, 2017b; Power et al., 2017).

This warning did not state whether there was a need to evacuate or specify if there was a land threat. CCC CDEM republished the warning, adding that they advised people to stay off the beaches. This led to confusion of the Banks Peninsula and Christchurch public who were noting that MCDEM websites were stating a need to evacuate, and were wondering why, if there was a tsunami risk, the sirens had not sounded (1:23 a.m.) (Kardos, 2017). Further messages were posted on the New Zealand Civil Defence (NZCD) Facebook page from the public who had observed that the NZCD website was saying there was no tsunami risk while also saying that the situation had changed, adding to additional confusion of the public (Kardos, 2017).

At 1:29 a.m., a second tsunami threat was issued by MCDEM (Kardos, 2017; MCDEM, 2017b). While this warning instructed people on the eastern coast of the North and South Islands, including the Chatham Islands, to move to inland or to higher ground immediately, it did not explicitly state if there was a threat to land (Kardos, 2017, MCDEM, 2017b). At this time, CCC CDEM were not yet asking residents to evacuate (Kardos, 2017). This decision was supported by knowledge of tsunami and the topography of Canterbury (Kardos, 2017; Schoenfeld, 2018). Contradicting this was information being released by RNZ (1:39 a.m.) – who were broadcasting that people needed to evacuate from coastal locations due to the risk of a 2 meter tsunami – and actions being completed by Christchurch Police (approximately 2:35 a.m.) – who under the instructions of the National Operations of Police, had activated their Coastal Evacuation Plan (Kardos, 2017; Lane et al., 2020).

Shortly after (2:01 a.m.), tsunami waves were detected on the Geonet tsunami gauges, prompting MCDEM to issue a tsunami warning stating that there was a threat to both marine and land areas (Kardos, 2017). As this warning included a risk to land, CCC CDEM instructed coastal communities in Christchurch and Banks Peninsula to evacuate. Following this, the decision was made to activate the tsunami sirens along the Christchurch coastline (2:07 a.m.) and a publication was made to social media to inform the population of the need to evacuate (Kardos, 2017; Schoenfeld, 2018). The decision to activate the tsunami sirens (which began sounding at 2:11 a.m.) was made despite the use of tsunami sirens for this kind of tsunami threat not being standard practice (Lane et al., 2020).

In communities along the northern coast of Banks Peninsula, the absence of tsunami sirens saw the activation of phone trees to be utilized as warning method (Lane et al., 2020; Schoenfeld, 2018).

In response to the evacuation, three evacuation centres were opened throughout the Christchurch City, and evacuees in Akaroa were welcomed to an evacuation centre (Kardos, 2017). To allow for the continued use of the sirens until there was no longer a land threat, it was requested that the sirens be activated every 15 minutes to prevent them from going flat (Kardos, 2017).

At 8:00 a.m. NZDT, the tsunami warning was revised to a land and beach warning, which saw the deactivation of the tsunami sirens in Christchurch (8:14 a.m. NZDT) and the end of the evacuation (Kardos, 2017).

Throughout this tsunami response there was confusion from the public. Contradicting information sources made it difficult for people to make a decision on the need to evacuate. There was confusion from the public who were unsure of their evacuation zones, whether they needed to evacuate, and the use of the sirens (Kardos, 2017; Lane et al., 2020; Schoenfeld, 2018). People also felt that the evacuation announcement took too (Kardos, 2017).

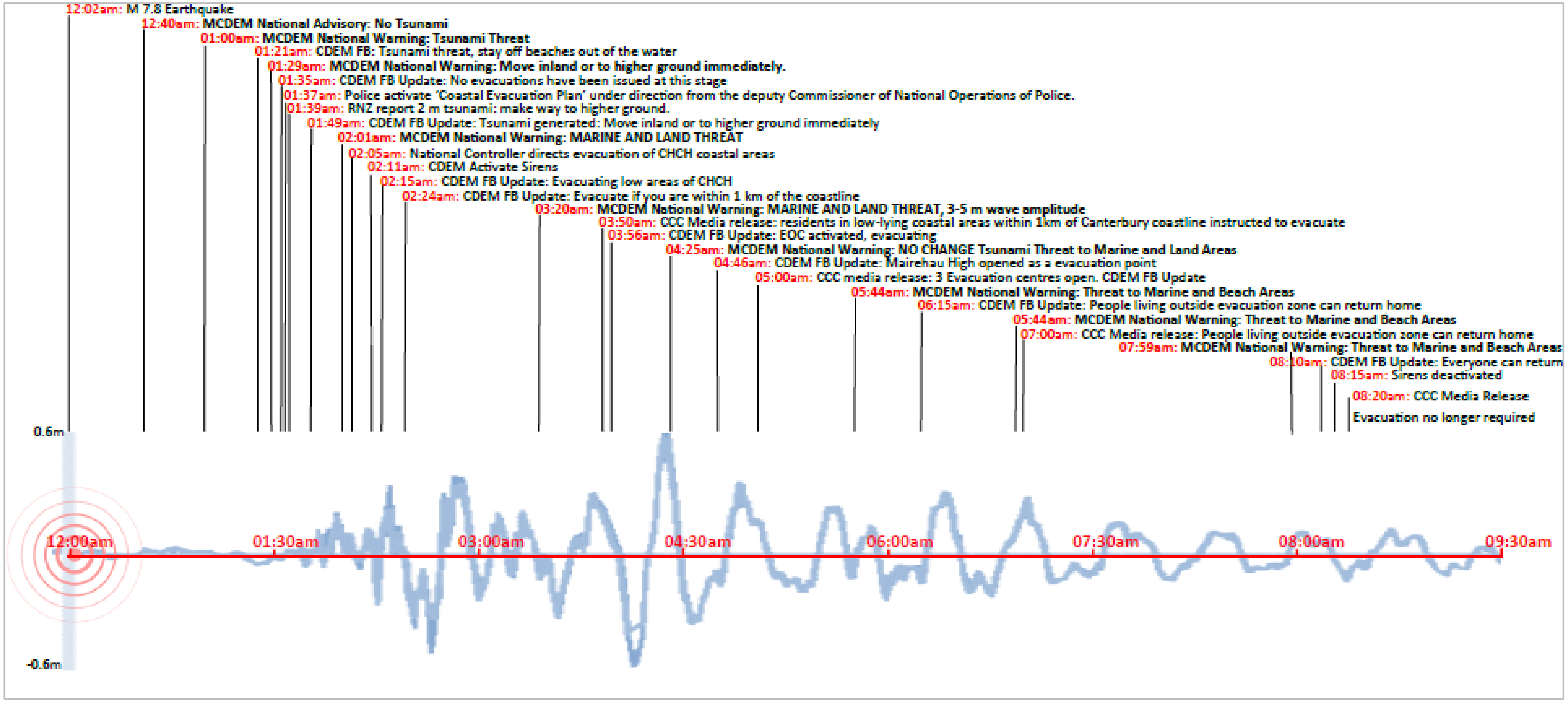

Figure 2.34: Timeline of the official response to the Kaikōura Earthquake against the Sumner tidal gauge (Thomas, 2017). The timeline starts at the time of the earthquake (approximately 12:00 a.m. November 14th 2016) and finishes after the evacuation order was no longer required (approximately 9:30 a.m. November 14th 2016). It shows the changing tsunami warnings, and the responses and messages disseminated by MCDEM, CCC and CCC and Canterbury CDEM.

2.5 GAPS IN RESEARCH

Recent global tsunami events have highlighted the importance of effective tsunami risk management strategies (including land-use planning, structural and natural defences, warning systems, education, and evacuation measures), however, the rarity of tsunami events means that there is comparatively much less literature and empirical data on reactions to tsunami warnings and evacuation behaviour than that for evacuations for other hazards (Arce et al., 2017; Fraser et al., 2016; Lindell & Prater, 2010; Makinoshima et al., 2020). Where tsunami evacuation behaviour studies have been conducted, the focus has largely been on whether people evacuated or not, rather focusing on the full evacuation process, including the response to warnings, pre-evacuation actions, evacuation dynamics and the return home which is more beneficial for improving evacuation planning (Makinoshima et al., 2020). Consequently, there is a lack of empirical data that can be used to inform evacuation planning and modelling that best represents how people react to warnings and behave during a tsunami evacuation (Kubisch et al., 2019; Makinoshima et al., 2016). Where evacuation modelling has been simulated, the focus has been the timings of the evacuation, instead of the behaviour of evacuees (Makinoshima et al., 2016). Further modelling has been simulated, but informed be reactions and behaviours during for other hazards such as hurricanes, where this data is more readily available (Fraser et al., 2013). While this may be useful for distant source tsunami due to the availability of time to assess the situation and conduct a managed evacuation, they may prove less useful for regional and local source tsunami where there is less time (Fraser et al., 2013).

This knowledge gap in understanding reactions to tsunami warnings and evacuation behaviour exists within New Zealand, where only a limited number of studies have bene conducted (Blake et al., 2018; Couling, 2014; Fraser et al., 2016). To minimize this knowledge gap, some studies have been conducted instead focusing on the actions people believe they would take in a tsunami event (Fraser et al., 2013). Specifically within Christchurch and Banks Peninsula, there have been very few tsunami that have prompted an evacuation, with the last major evacuation being in 1960 (Johnston et al., 2008). Although tsunami risk management strategies have been implemented within these areas, the infrequency of tsunami means there have been few opportunities to test these strategies. Consequently, there is little data on how people in Christchurch and Banks Peninsula respond to the tsunami warnings and behave during a tsunami evacuation. Only one study has been conducted on tsunami awareness and intended evacuation behaviour within Christchurch and Banks Peninsula (DuBois, 2007). While tsunami evacuation models have been developed for coastal areas of New Zealand (Fraser et al., 2014; Knook et al., 2015), including areas of Christchurch (Le, 2016; Power et al., 2019; Tilley, 2018), the rarity of tsunami evacuations and subsequent empirical data on behaviours and responses means that there has not been an opportunity to inform modelling. Additionally, no evacuation modelling has been performed for Banks Peninsula.

The tsunami generated during the 2016 Kaikōura Earthquake provided an opportunity to assess how the coastal populations of Christchurch and Banks Peninsula reacted to the tsunami warnings and their decisions made during this evacuation. This information can provide a comprehensive overview and understanding of the full evacuation process taken by evacuees during this event, including data such as the response to warnings, pre-evacuation actions, evacuation movement and the return home Assessing the evacuation dynamics associated with this evacuation can improve local, national and global understanding of factors that affect these dynamics. This knowledge can contribute to tsunami preparedness and risk management strategies including evacuation planning and education strategies. This research can also help inform evacuation planning, by developing an evacuation model for coastal communities, where the modelling is informed by the survey responses to create a more realistic evacuation model.

3 CHRISTCHURCH AND BANKS PENINSULA EVACUATION BEHAVIOUR SURVEY

3.1 INTRODUCTION

This chapter addresses Objective 2 of the thesis: Analysis of behaviour and actions to the 2016 Kaikōura earthquake and tsunami. The chapter is structured by first presenting the methodology of the development and utilisation of a survey instrument designed to understand the reaction and evacuation behaviour of how people reacted and behaved in the 2016 tsunami evacuation warning. Following this the survey results are presented. This is followed by a discussion of the key themes of the results, drawing on global and local evacuations from tsunami and other hazards. Finally, the key limitations, recommendations and suggestions for future work are discussed

3.2 METHOD

Survey questionnaires are a popular tool for gathering information relating to characteristics, behaviours, attitudes, and beliefs (Bird, 2009; Dillman et al., 2014; Gillham, 2008). Survey questionnaires have been used by a range of groups or agencies, including educators, interest groups, government agencies, scientists, and non-profit foundations (Dillman et al., 2014). The use of survey questionnaires is based on the need to solve a problem or answer a question, thus, they have been used to gain information on a variety of topics. They are a well-established tool that for post-disaster studies, and allow researchers and emergency managers to gain an understanding of people's behaviour and reactions during an event such as a tsunami evacuation (Bird, 2009; Bird et al., 2011). Examples of the use of post-disaster survey questionnaires following recent tsunami events have been outlined by Harnantyari et al. (2019) and Mas et al. (2015). For this research, a survey questionnaire was used to improve understanding of how people in Banks Peninsula and Christchurch reacted to tsunami warnings during the 2016 Kaikōura earthquake tsunami, and their actions and behaviour during this event. Rather than focus only on how coastal residents interpreted the earthquake shaking and their evacuation decisions, the survey included questions relating to the full evacuation process including the reactions to warnings, and evacuation movements and timings. Including these questions in tsunami evacuation behaviour questionnaires has been identified as being crucial to create a comprehensive overview of the evacuation process to improve future risk management strategies (Makinoshima et al., 2020).

This research, requested by CCC CDEM and Canterbury CDEM approximately two years after the earthquake and tsunami evacuation, falls into a wider research project to understand evacuation dynamics during the 2016 Kaikōura earthquake tsunami evacuation for other communities in Canterbury including Kaikōura (Tilley, 2020).

3.2.1 Survey Development

The basis of the survey questionnaire was a survey that had been developed by Blake et al. (2018) which aimed to assess the preparedness and evacuation behaviour of those in Petone and Eastbourne, Wellington, during the 2016 Kaikōura earthquake tsunami. This survey was an adaption of a tsunami risk and preparedness survey questionnaire developed by Johnston et al. (2003) for research conducted by GNS Science focusing on knowledge of tsunami risk, warnings, what to do during a tsunami, preparedness and how this had changed following the 2004 Boxing Day tsunami. The survey developed by Johnston et al. (2003) has been influential in the development and focus of other tsunami awareness surveys that have been distributed throughout New Zealand (including Blake et al., 2018; Currie et al., 2014; Dhellemmes et al., 2016; Fraser et al., 2013). For the purpose of this research, the survey questions were modified to allow for a geospatial science approach with a focus on evacuation dynamics. Questions added included:

- What sources of information did you use to decide to evacuate or not?
- Did you encounter any traffic congestion or were you aware of congestion problems (with follow up questions regarding the congestion sped, location and time)?
- Where were you when the earthquake occurred on Monday 14th November 2016 at 12.02 a.m.?
- Where did you evacuate to?
- Please draw your evacuation route.
- Changes in risk awareness, preparedness and knowledge of tsunami hazards before and after the 2016 evacuation.

The survey questionnaire included a total of 40 questions and aimed to gain an understanding of how people reacted to the tsunami warning sources, their evacuation decisions, where and how they evacuated, congestion they observed or encountered, and how their knowledge of tsunami hazards and risk influenced their behaviour during this evacuation. A location-specific map for each community was added into the survey to produce spatial results relating to respondents evacuation movement. The survey was designed for distribution to residents of Banks Peninsula and Christchurch who were in these locations during the 2016 Kaikōura earthquake tsunami. The full survey questionnaire can be viewed in Appendix A.

3.2.2 Survey Distribution

Fourteen communities in Christchurch and Banks Peninsula were surveyed (Figure 3.1). This included Sumner, Redcliffs, Mount Pleasant, North Brighton, New Brighton, South Brighton, and Southshore (Christchurch) and Lyttleton, Teddington, Okains Bay, Le Bons Bay, Little Akaloa, Akaroa, and Birdlings Flat (Banks Peninsula). These communities were selected based on advice from the local (CCC) and regional councils (Environment Canterbury (ECan)). Demographic information relating to these communities can be viewed in Table 3.1.

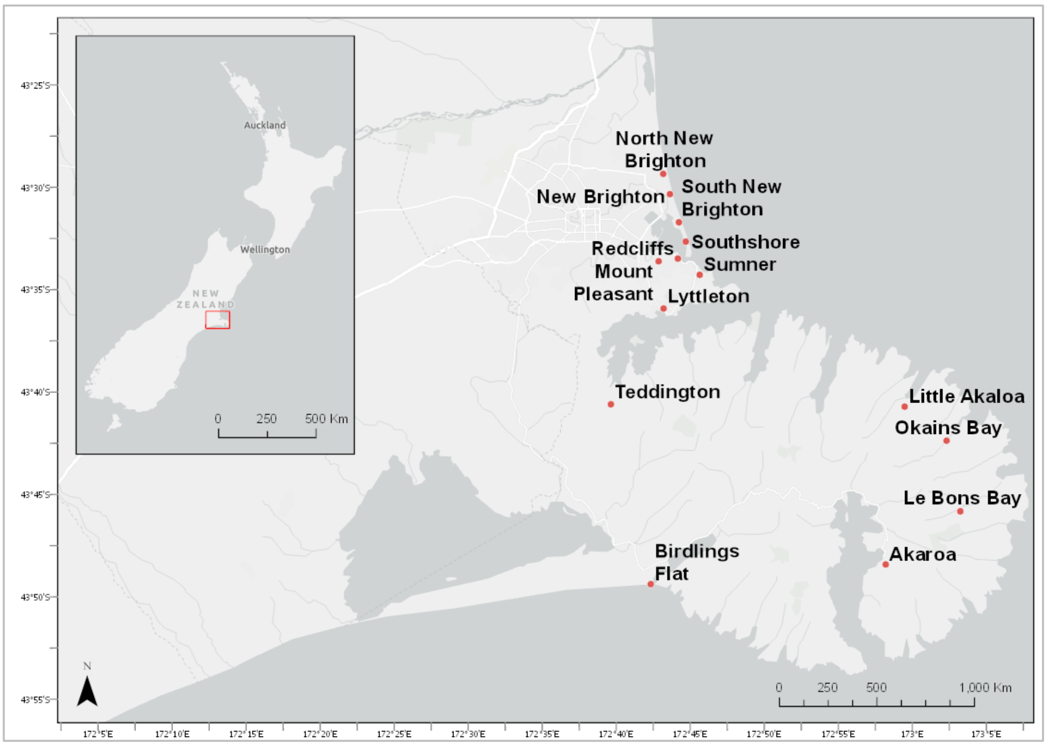

Figure 3.1: Locations of the 14 surveyed communities.

*Table 3.1: Census information for Banks Peninsula and Christchurch** (CCC, n.d.a).*

Community	Banks Peninsula Ward	Coastal Ward (North Brighton, New Brighton, South Brighton and Southshore)	Heathcote Ward (Sumner, Redcliffs, and Mount Pleasant)
Population (2013)	8,580	24,200	24,200
Population (2018)	8,710	25,100	25,700
Gender (2013)	Male – 49.1% Female – 51.0%	Male – 48.7% Female – 51.3%	Male – 49.1% Female – 50.9%
Median age (2013)	47.2	39.3	42.1
Average household size (2013)	2.3	2.5	2.4
Median household income (2013)	$32,200	$30,300	$34,000
Number of households (2013)	3,470	8,970	9,260

**Note: Both 2013 and 2018 data have been included due to data not yet being released from the 2018 Census for these three wards. It is important to note that for the 2018 Census there was an increase in non-respondents and in the attempt to go digital, there were also accessibility issues (Dashfield, 2018). Further to this, it has been recognised by Stats NZ that there ware data quality issues with the 2018 data (Stats NZ, 2019).

Both an online and a hard-copy survey questionnaire were used as survey distribution methods for this study. While there are many reasons multiple methods of survey distribution can be used (including reducing error), for this research, a multi-method survey distribution approach was chosen with the aim of increasing survey reach and maximising the number of returns (Dillman et al., 2014). The purpose of this was to record a higher number of evacuation routes to improve understanding of the evacuation dynamics during this event. The primary distribution method was a hard-copy survey letterbox drop that included a survey package with the survey, an information sheet and a pre-paid envelope to encourage participants to return the survey. In Sumner, the hard-copy survey was also distributed using snowball sampling (survey respondents distributing the survey to their acquaintances who further distribute the survey amongst acquaintances), word-of-mouth and static sampling at the local supermarket. An online survey link was also sent to community groups in Christchurch to be published in email newsletters and on Facebook pages. A survey link was also published in a local newspaper (Pegasus Post, 2018), enabling the survey to reach communities that were not initially included in the study.

Through October and December 2018, 1,773 hard-copy survey questionnaires were distributed. The distribution of the survey questionnaire was requested by local authorities approximately two years after the earthquake and tsunami evacuation. The survey distribution primarily focused on residential properties within the three evacuation zones close to the shore. Surveys were also distributed to some residential properties outside of the evacuation zones to assess if people were aware of their evacuation zones and the need to evacuate depending on the tsunami risk. The frequency of survey distribution to households varied on the size of the community, balancing the need to sample efficiently and representatively. In the smaller communities of Banks Peninsula all houses were distributed a hard-copy survey in their mailbox, whereas in the larger communities of Christchurch fewer houses were targeted (Table 3.2). Appendix B provides details on where the surveys were distributed in each community.

Table 3.2: Survey distribution methodology and rate of distribution based on area unit. Note that the communities have been put into their meshblock groups where, South Brighton includes South Brighton and Southshore, Governors Bay includes Teddington, and Little River includes Birdlings Flat.

Suburb	Distribution Methodology	Surveys Distributed	Distribution Rate (within area unit of community) (%)
Akaroa	Every House	100	34%
Governors Bay	Every House	20	6%
Le Bons Bay	Every House	20	44%
Little Akaloa	Every House	24	62%
Little River	Every House	90	20%
Lyttelton	Every 7th House	100	8%
Mount Pleasant	Every 7th House	94	8%
New Brighton	Every 7th House	455	44%
North Brighton	Every 7th House	259	4%
Okains Bay	Every House	20	56%
Redcliffs	Every 7th House	79	7%
South Brighton	Every 7th House	212	16%
Sumner	Every 3rd House	300	22%
Total Survey Distribution		1773	

This research was conducted following the guidelines of the University of Canterbury Human Ethics Committee (approval codes: HEC 2017/29/LR-PS; HEC 2018/42/LR/PS; see Appendix C).

3.3 Results

This section presents the results of the evacuation behaviour survey questionnaire. Details regarding the return rate of the survey questionnaires are presented first, followed by the demographics of the survey respondents. The survey results have been divided into three key themes. First is the initial reactions to the earthquake and the warning sources used during the 2016 Kaikōura earthquake and tsunami. This section is followed by respondent's evacuation behaviour, including pre-evacuation actions, evacuation decisions, and evacuation dynamics. Finally details on survey respondent's changes in tsunami preparedness and knowledge are presented. The full results of the evacuation behaviour survey questionnaire can be viewed in Appendix D.

Two-hundred and six surveys were returned from the studied communities, giving a return rate of 11.6%, however, both the online and the hard-copy surveys reached participants that were beyond the studied communities which increased the total number of surveys returned to 220, giving a total return rate of 12.4% (Table 3.3). The return rate of surveys in Christchurch was 13.7%, while for Banks Peninsula was 7.5% (Table 3.4). This consisted of 70 online and 150 hard-copy surveys (Table 3.5).

Table 3.3: Return rate of surveys in study areas. Note that the communities have been put into their area unit groups where South Brighton includes South Brighton and Southshore, Governors Bay includes Teddington, and Little River includes Birdlings Flat.

Suburb	**Distribution Rate (%)**	**Total Returns**	**Return Rate (%)**
Akaroa	34%	5	5%
Governors Bay	6%	1	5%
Le Bons Bay	44%	1	5%
Little Akaloa	62%	1	4%
Little River	20%	16	18%
Lyttelton	8%	2	2%
Mount Pleasant	8%	11	12%
New Brighton	44%	35	8%
North Brighton	4%	23	9%
Okains Bay	56%	1	5%
Redcliffs	7%	22	28%
South Brighton	16%	35	17%
Sumner	22%	53	18%
Total Survey Return Rate for Studied Communities		206	11.6%
Total Survey Return Rate Beyond Studied Communities		220	12.4%

Table 3.4: Details on the number of surveys distributed and returned for Christchurch and Banks Peninsula.

Location	**Surveys distributed**	**Surveys returned**	**Return rate**
Christchurch	1399	192	13.7%
Banks Peninsula	374	28	7.5%
Total	1773	220	12.4%

Table 3.5: Number of hard-copy and online surveys that were returned. Note that suburbs with an asterisk indicate they were not the main communities of interest for this study.

Suburb	**Hard-Copy Returns**	**Online Returns**
Akaroa	5	0
Aranui*	0	1
Birdlings Flat	15	1
Cass Bay*	1	0
Le Bons Bay	1	0
Little Akaloa	1	0
Lyttleton	2	0
Mount Pleasant	9	2
New Brighton	26	9
North Brighton	21	2
Okains Bay	1	0
Parklands*	0	2
Redcliffs	6	16
South Brighton	7	20
Southshore	5	3
St Albans*	1	0
Sumner	48	5
Teddington	1	0
Waimairi Beach*	0	7
Waimak*	0	1
Woolston*	0	1
Total	150	70

There were 28 Banks Peninsula respondents (13% of the total) and 192 Christchurch respondents (87% of the total). The majority of survey respondents were female (Table 3.6). The age of survey respondents ranged from 28 to 88 years old, with the mean being 57 years (Table 3.7). Over half of the survey respondents identified as living in a family either with children (41%) or without children (35%) (Table 3.8).

Table 3.6: Gender of survey respondents.

	Female	Male	Gender diverse	
Banks Peninsula	9% (n=18)	27% (n=7)	1% (n=1)	
Christchurch	53% (n=105)	39% (n=68)	0	
Total	62% (n=123)	38% (n=75)	1% (n=1)	100% (n=199)

Table 3.7: Age of survey respondents.

Age	Count	Percent
Less than 30	1	0%
30-40	21	10%
40-50	34	15%
50-60	45	20%
60-70	38	17%
70-80	28	13%
80-90	9	4%
More than 90	0	0%
Prefer not to disclose/did not answer	44	20%
Total	220	100%

Table 3.8: Living situation of survey respondents.

Living Situation	Count	%
Family with Children	80	41%
Family without children	68	35%
Alone	39	20%
With non-family	8	4%
Prefer not to disclose	2	1%
Total	197	100%

3.3.1 Initial Reactions to Earthquake & Tsunami Warning Sources

This section presents the survey respondents' initial reactions to the earthquake, including shaking duration and intensity, and the tsunami warning sources respondents used to inform their evacuation decisions.

3.3.1.1 Initial Reactions to the Kaikōura Earthquake

Most of the survey respondents were reported being awoken by the Kaikōura earthquake (80%, n=166). Of the total respondents, 14% (n=30) were already awake, while only 6% (n=12) were not woken and slept through the shaking.

Survey respondents were asked to record the intensity that they perceived the earthquake shaking to be. For the purpose of this research and the survey questionnaire, these intensities were listed as qualitative terms that the public could relate to. These have then been converted into Modified Mercalli intensity values (Geonet, n.d.b) to allow the intensities to be compared to other studies (see Appendix E for further details). More than half of the total survey respondents felt the Kaikōura earthquake shaking intensity to be moderate (MMI 5) (58%, n=120), while almost 20% (n=40) felt it to be strong to powerful (MMI 6-7). A further 6% (n=12) felt the shaking was violent to severe (MMI 8-12). Thirteen percent (n=26) described the shaking intensity as a jolt or mild (MMI 4), while 2% (n=4) felt it as gentle (MMI 3), and 3% (n=6) did not feel the earthquake (MMI 1-2).

A higher percentage of respondents from Christchurch felt the shaking to be strong to powerful, while more people from Banks Peninsula felt the shaking to be violent to severe (Figure 3.2).

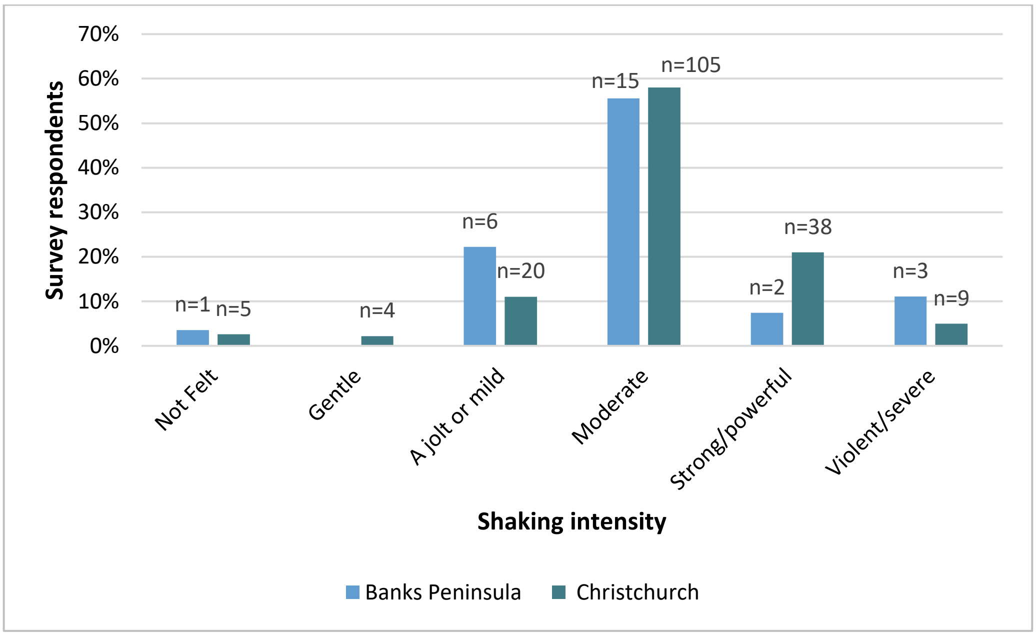

Figure 3.2: Perceived shaking intensity felt by survey respondents (n=208).

The majority of survey respondents perceived the earthquake shaking duration to be 60 seconds or less (59%, n=122). Eighteen percent (n=37) of the total respondents perceived the shaking to be longer than 60 seconds. Only 11% (n=23) felt the shaking duration was 120 seconds or longer. A further 21% (n=43) didn't know how long the shaking duration was, while 2% (n=5) did not feel the earthquake (Figure 3.3).

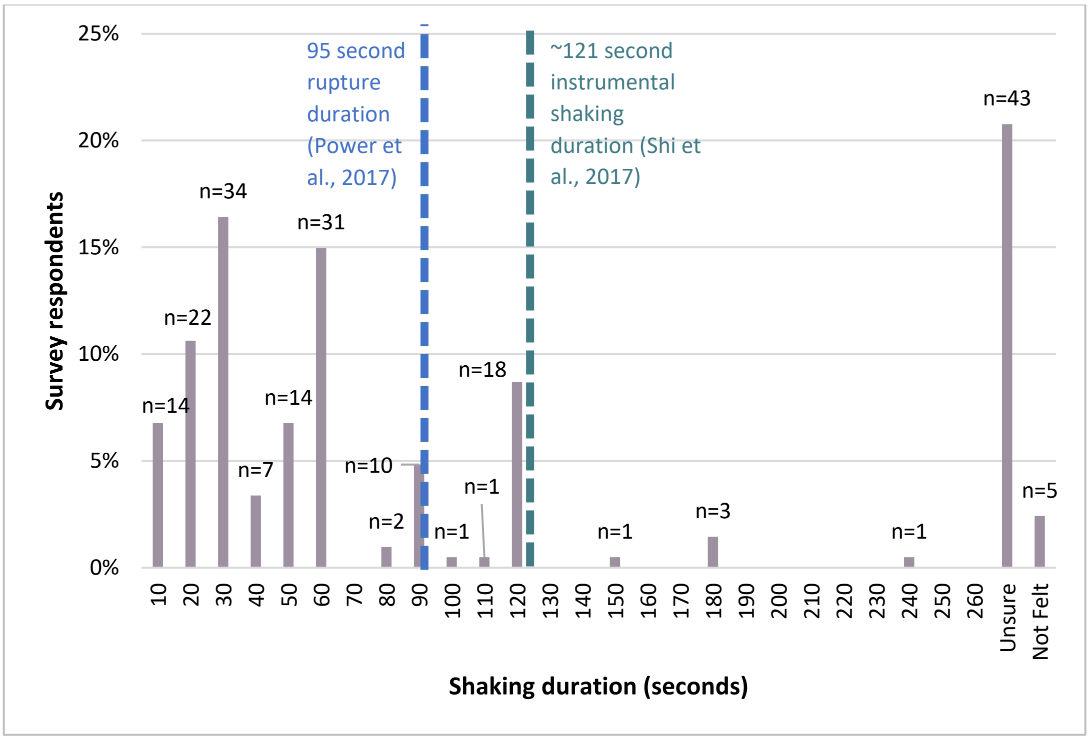

Figure 3.3: Perceived shaking duration in seconds felt by respondents. Rupture duration and instrumental shaking duration have been added onto the graph (n=207).

Respondents were asked to record the actions they took following the earthquake shaking, as shown below in Table 3.9. A compilation of frequent words used by respondents representing actions taken can be seen below in Figure 3.4 (note that as responses have been grouped by action, the percentage does not add to 100%). Following the shaking, 50% (n=97) of the survey respondents commented that they sought further information from sources including social media, the radio, TV, GeoNet/GNS Science, and local or national authorities. Twenty-two percent (n=43) went back to sleep, while only 6% (n=12) of the respondents commented that they evacuated immediately (Table 3.9).

Table 3.9: Actions taken by respondents after the earthquake shaking had stopped (n=194). Note – responses have been grouped by actions and themes so the percentage does not add to 100%.

Action	Count	%
Went back to sleep	43	22%
Sought further information	97	50%
Check household members or contact others	53	27%
Check outside	3	2%
Evacuate	12	6%
Locate emergency items	1	1%
Check the house for damage	8	4%
Check pets	6	3%

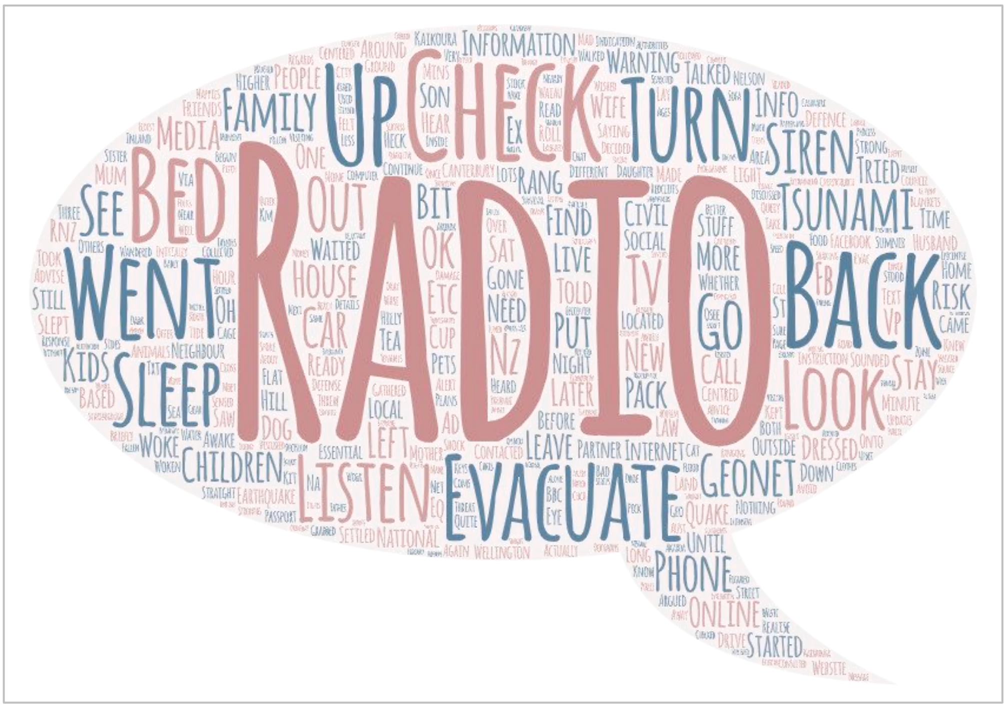

Figure 3.4: Word cloud representing the qualitative answers given by respondents when asked to record their actions after the earthquake shaking had stopped. Words that are shown larger in the figure were more frequently used by respondents.

3.3.1.2 Warning Sources Recognised by Respondents

Survey respondents were asked to select all of the warning sources that warned them of a possible tsunami. Thirty-eight percent (n=77) of the total respondents stated that they were warned by the earthquake shaking. Many people relied on some form of official warnings, such as messages over the radio, television and social media disseminated from CDEM (34%, n=69) or the activation of the tsunami sirens (41%, n=85). Family and household members warned 14% (n=28) of the total respondents, while 16% (n=33) were warned by other community members. Other warning sources people used included radio, internet, social media, and family and friends living elsewhere.

A similar proportion of the survey respondents from Banks Peninsula and Christchurch identified that official warnings such messages over the radio, television, and social media from CDEM, and the earthquake shaking warned them of a potential tsunami (Figure 3.5). Of the total respondents from Banks Peninsula, 15% (n=4) did not think a tsunami would be possible during this tsunami evacuation, with comments including "*I heard the quake was in Kaikōura and decided there was no tsunami risk", "there was no need to as there was no danger*" and "*understood that Birdlings Flat was at lower risk due to the peninsula and is more at risk from Chile".* Only 3% (n=5) of respondents from Christchurch never thought/ have never been aware there could be a tsunami did. Note that multiple warning sources could be selected for this survey question.

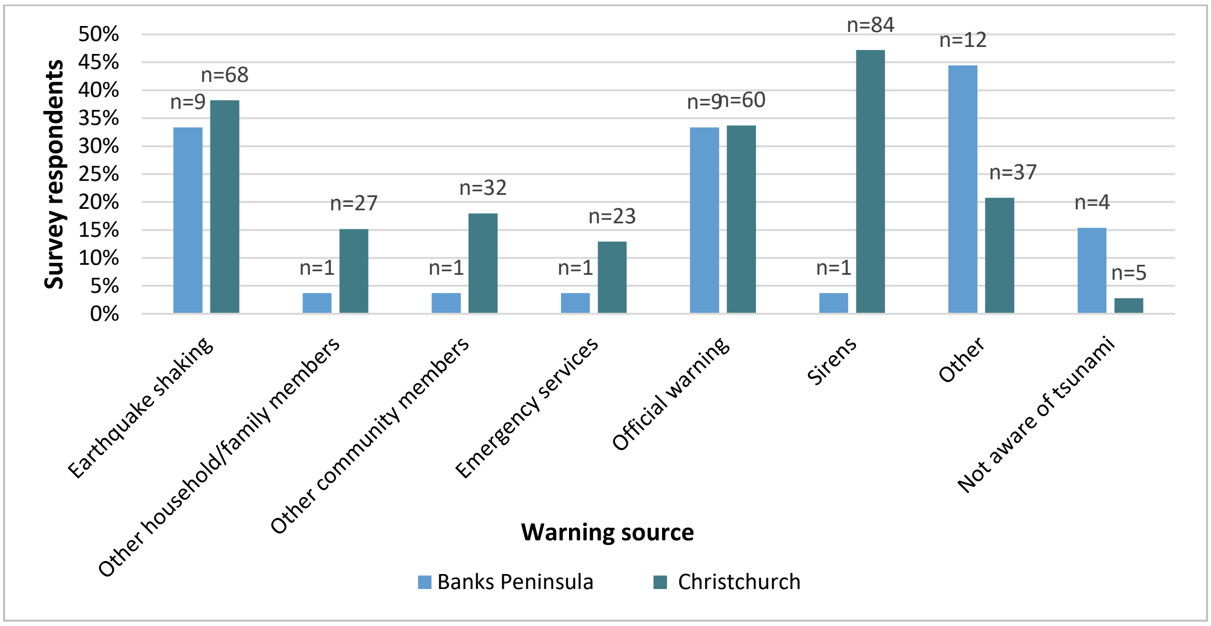

Figure 3.5: Recognised warning sources for a potential tsunami (n=205). Note – survey respondents could select multiple warning sources for this question.

Of the survey respondents who felt the shaking from the Kaikōura earthquake, 38% (n=77) recognised the earthquake as a warning source for a potential tsunami (Figure 3.6). Forty-one percent of these respondents recognised the sirens as a warning source (n=82). Only 3% (n=7) of these respondents never thought/ have never been aware there could be a tsunami. Note that multiple warning sources could be selected for this survey question.

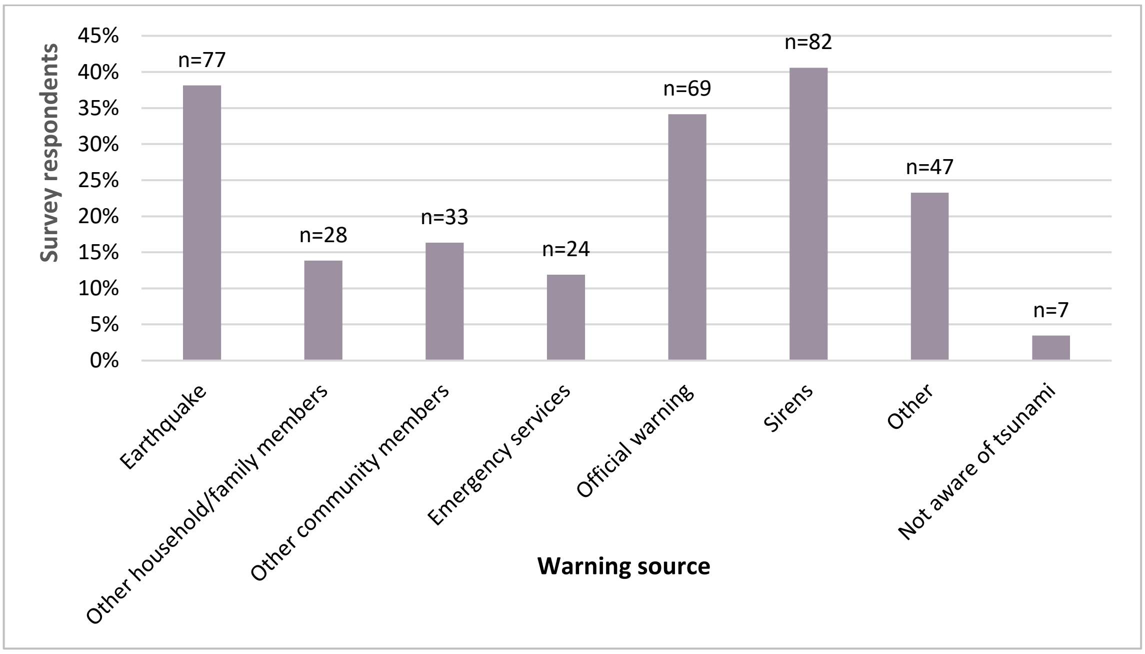

Figure 3.6: Warning sources recognised by survey respondents who felt the earthquake shaking (n=202). Note – survey respondents could select multiple warning sources for this question.

A higher proportion of females were warned of a potential tsunami by community members (24%, n=29) and household/family members (17%, n=21) than males (4%, n=3 and 9%, n=7), while more males recognised the tsunami siren as a warning source (49%, n=36) than females (37%, n=46) (Figure 3.7). A similar proportion of families who were living with and without children recognised the official warnings released by MCDEM (including radio, television, and social media messaging) as a warning source (36%, n=29 and 34%, n=23) (Figure 3.8).

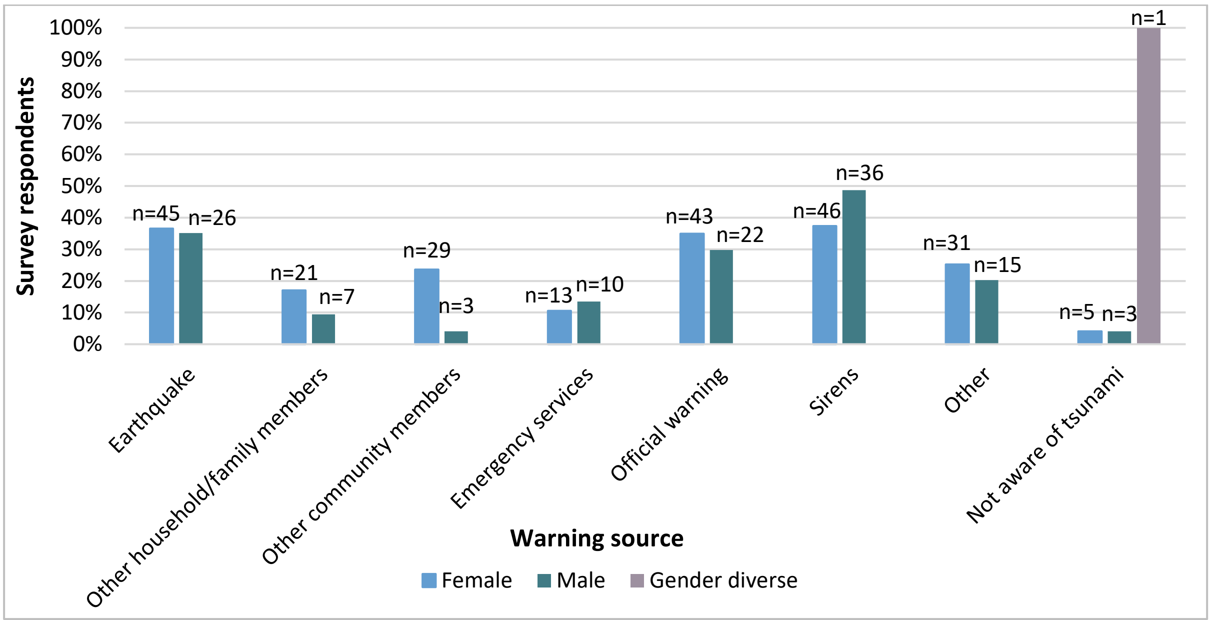

Figure 3.7: Warning sources recognised by those who identify as female, male and gender diverse (n=195). Note – survey respondents could select multiple warning sources for this question.

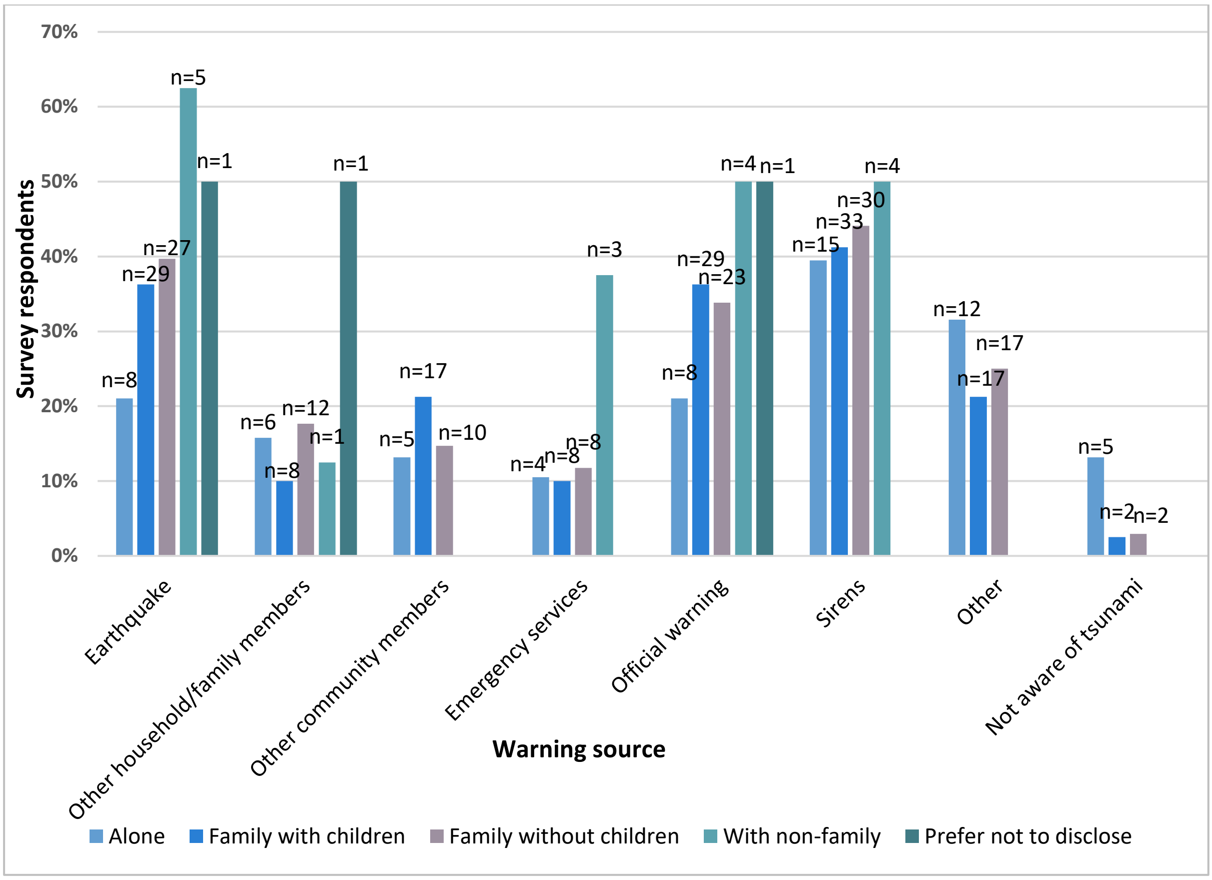

Figure 3.8: Warning sources recognised by living situation of respondents (n=194). Note survey respondents could select multiple warning sources for this question.

Survey respondents were asked to select the main warning source that made them evacuate. More than a quarter (29%, n=47) evacuated because of official warnings from Civil Defence, while a further 16% (n=26) evacuated because of the tsunami sirens. Twenty-four percent (n=40) of respondents evacuated because of the earthquake, with 19% (n=31) evacuating because of other household, family and community members.

3.3.2 Evacuation Behaviour

This section outlines respondents' behaviour during the evacuation process. This includes the decision making process to decide whether to evacuate, actions taken prior to evacuating, and general evacuation dynamics relating to mode of transportation, the time respondents evacuated, and evacuation routes.

3.3.2.1 Actions Taken Before Evacuating

Survey respondents were asked to select all of the actions they completed before evacuating. Shown in Figure 3.9, in both Christchurch and Banks Peninsula, the common evacuation process consisted of gathering household family members (48%, n=81), seeking further official information (39%, n=66), gathering pets (36%, n=61), contacting friends and family (32%, n=53), gathering life essentials (30%, n=51), and discussing evacuation plans (24%, n=45). A further 17% (n=29) assisted others in evacuating, however this was more common in Christchurch (Figure 3.9). Only 10% (n=17) of the total respondents, all of whom were from Christchurch (Figure 3.9), reported that they did not partake in any pre-evacuation actions and evacuated immediately. Of those who evacuated immediately, 47% (n=8) lived in a family without children, while 24% (n=4) lived alone (Figure 3.10). Sixty-five percent (n=11) of those who evacuated immediately were in the orange evacuation zone (Table 3.10).

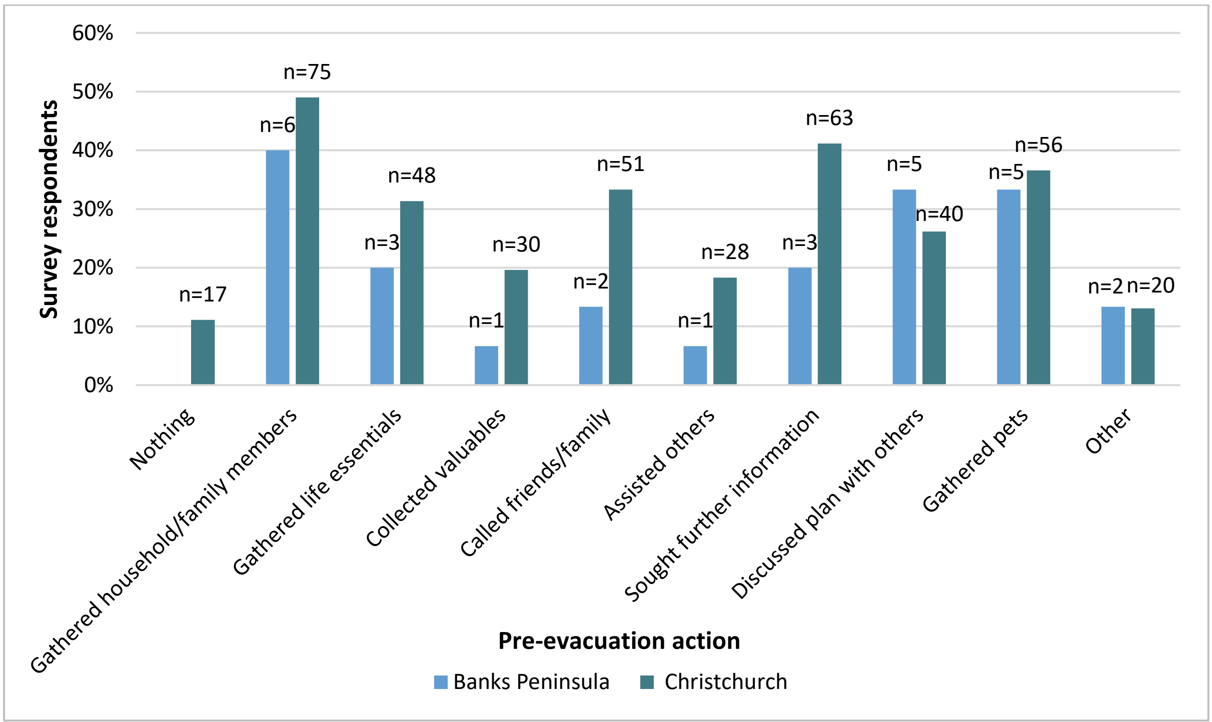

Figure 3.9: Actions taken by respondents in Banks Peninsula and Christchurch prior to evacuating (n=168).

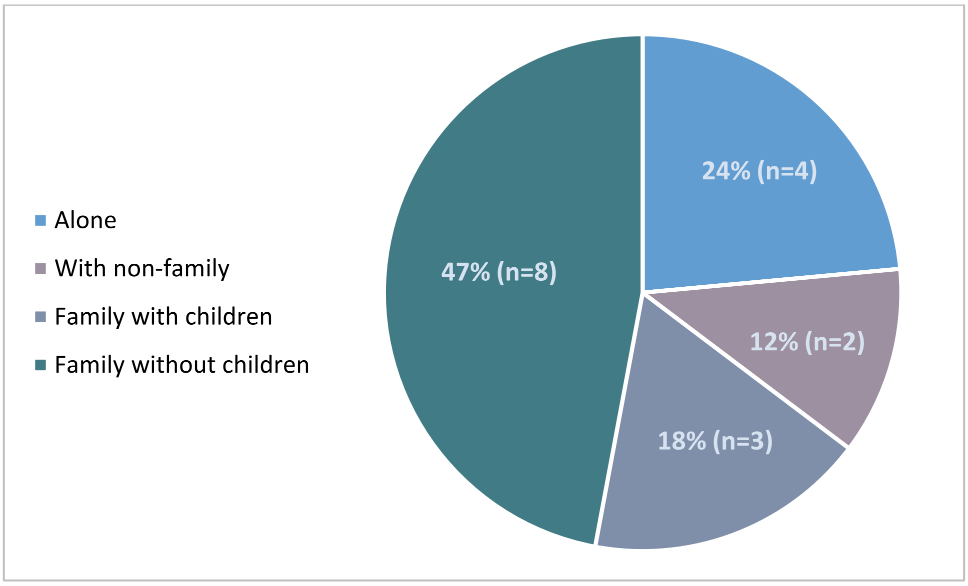

Figure 3.10: Living situation of respondents who did not partake in any pre-evacuation actions and evacuated immediately during the 2016 Kaikōura earthquake tsunami (n=17).

Table 3.10: Evacuation zone respondents who evacuated immediately originated from during the 2016 Kaikōura earthquake tsunami.

Evacuation zone	Number who evacuated from zone	Percent
Red	0	0%
Orange	11	65%
Yellow	2	12%
Outside of evacuation zone	1	6%
No origin point provided	3	18%
Total	17	100%

Thirty-seven percent (n=60) of all survey respondents reported that they took between 1 and 10 minutes to get ready to evacuate. It took 31% (n=50) of all respondents between 10 and 30 minutes to evacuate and 29% (n=47) between 30 minutes and 3 hours to get ready to evacuate. Only 1% (n=2) of all survey respondents took less than one minute to get ready to evacuate.

3.3.2.2 Evacuation Decision

Of the total 220 responses, 144 respondents recorded that they evacuated their homes at some point during the 2016 Kaikōura earthquake tsunami. This is an evacuation rate of 65%. An additional 17 respondents who either stated that they did not evacuate or left the question blank, answered the remainder of the survey as if they had evacuated. Including these responses brings the total number of respondents who evacuated to 161 with a rate of 73% (Figure 3.11).

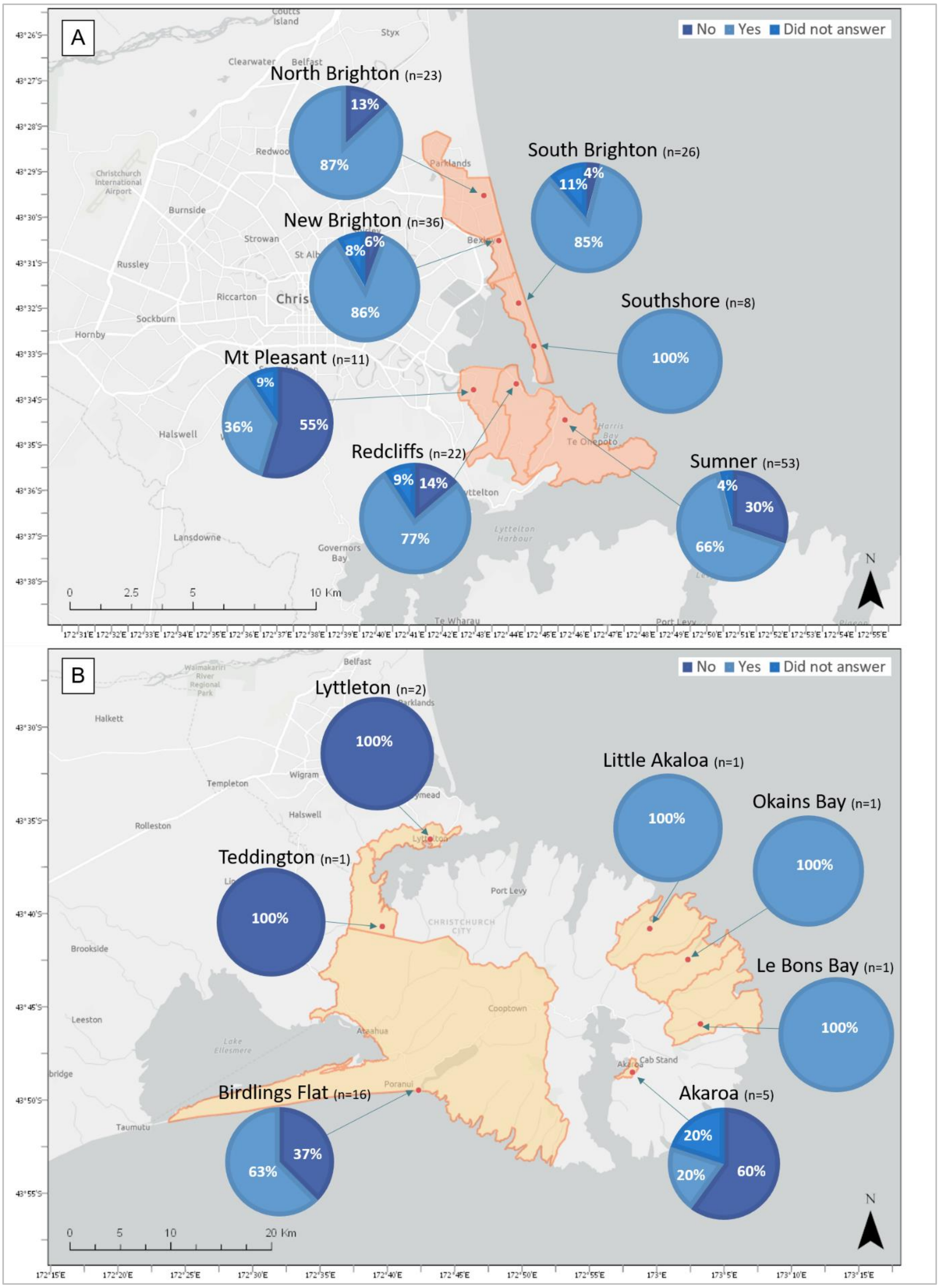

Figure 3.11: Percentage of survey respondents in surveyed communities of Christchurch (A) and Banks Peninsula (B) who did or did not evacuate.

Shown below in Figure 3.12, the overall evacuation rate in Banks Peninsula was 50% (n=13), while for Christchurch it was 83% (n=148).

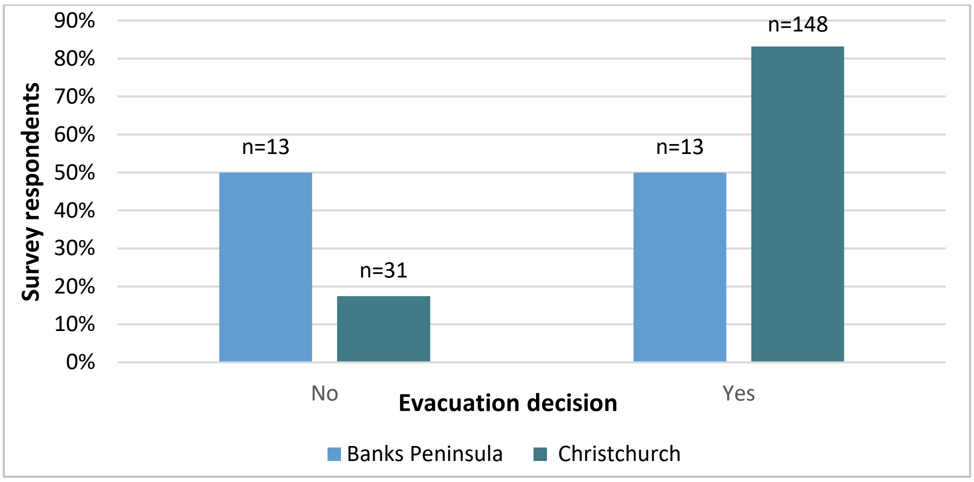

Figure 3.12: Proportion of respondents from Banks Peninsula and Christchurch who did or did not evacuate (n=178).

The highest proportion of respondents who evacuated and identified their living situation were living as a family with children (45%, n=62) (Figure 3.13). A higher proportion of respondents from all living situations, apart from those who preferred not to disclose their living situation, reported that they evacuated, when compared to those for each situation who did not evacuate (Figure 3.14). For example, 71% (n=5) of respondents who were living with non-family evacuated while 29% (n=2) did not (Figure 3.14). The results shown in Figure 3.13 are representative of the demographics of the survey respondents outlined in Table 3.8.

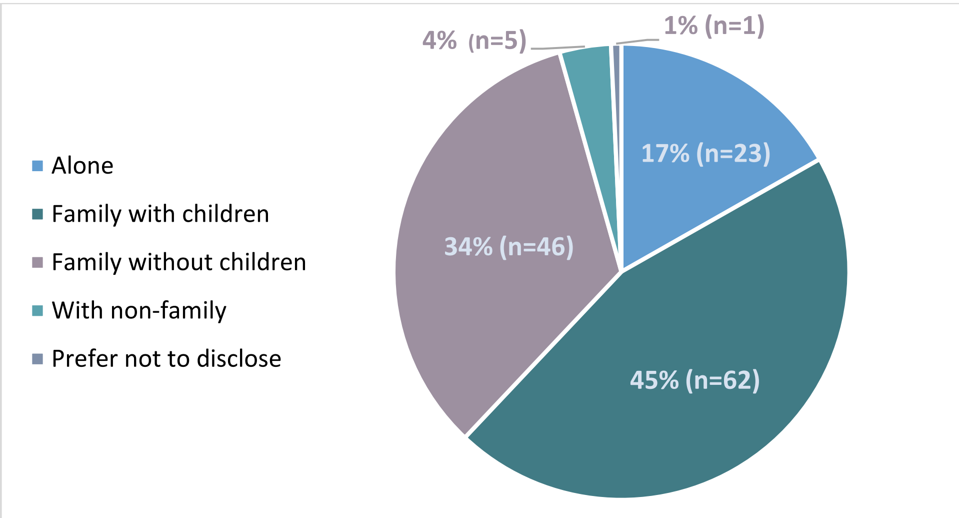

Figure 3.13: Proportion of survey respondents who evacuated from each living situation (n=137).

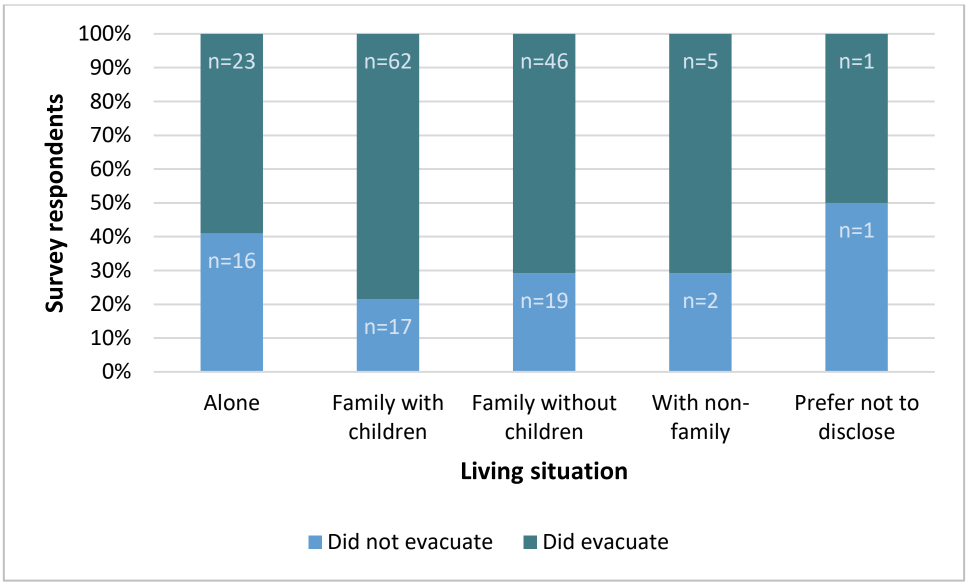

Figure 3.14: Percentage of respondents for each living situation who did or did not evacuate during the tsunami evacuation (n=204).

Figure 3.15 combines the evacuation rate with the perceived shaking duration and intensity. Twenty-eight percent (n=44) of respondents recalled the shaking duration was between 40-60 seconds, with 15% (n=24) of these respondents perceiving the shaking intensity to be moderate. As can be seen by the red point representing the proportion who evacuated for each shaking duration, 82% (n=36) of these respondents evacuated (Figure 3.15). In contrast, 3% (n=5) of respondents recalled the shaking lasted over 121 seconds, with 2% (n=3) of these respondents perceiving the intensity to be moderate and a further 1% (n=1) perceiving it to be violent/severe. The evacuation rate of these respondents was 60% (n=3) (as shown in Figure 3.15).

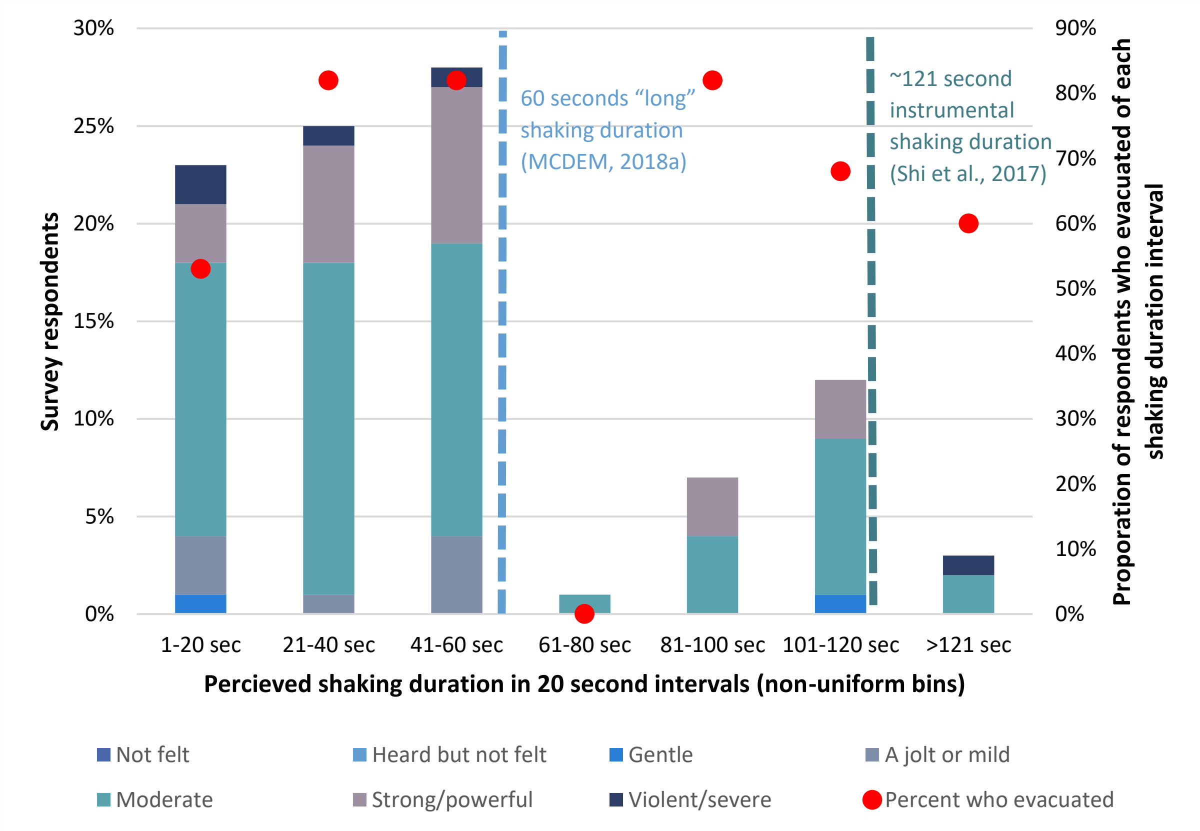

Figure 3.15: Percentage of survey respondents who evacuated, against the perceived shaking intensity and the shaking duration (n=157). The perceived shaking duration has been grouped into 20 second intervals. The perceived shaking intensity perceived by respondents is presented for each respective shaking duration (left Y-axis). The proportion of respondents who evacuated for each shaking duration is also presented. For reference, a marker of 60 seconds shaking duration has been added, denoting the threshold for communities in evacuation zones to evacuate from NZ tsunami evacuation public education messaging (MCDEM, 2018a). A mark is also presented of the shaking duration of the Kaikōura earthquake recorded from seismograph instruments (Shi et al., 2017).

Seven percent (n=10) of the total respondents who evacuated did so for reasons other than the tsunami. This included being asked to leave by police, and concern from family, friends and neighbours. Three percent (n=4) evacuated because of the tsunami sirens, while a further 2% (n=3) reported that they evacuated because of the disruption of the noise from the sirens, rather than the tsunami threat itself. This was reported in New Brighton and South Brighton where tsunami sirens are present along the beach. Reasons for not evacuating included a lack of transport, the initial statement that there was no tsunami risk, an initial absence of tsunami sirens, and the shaking not feeling strong enough to generate a tsunami.

3.3.2.3 Multiple Evacuation

Eight percent (n=12) of respondents reported that they evacuated more than once. Eleven of these respondents were from Christchurch communities (Redcliffs, Sumner, New Brighton, and South Brighton), while one was from Banks Peninsula (Le Bons Bay). Seven of those who evacuated more than once identified as living in a family without children (Figure 3.16). No one who had identified as living alone or preferred not to disclose their living situation reported evacuating multiple times. As seen in Figure 3.17, a slightly higher proportion of male survey respondents evacuated multiple times (58%, n=7) compared to female respondents (42%, n=5).

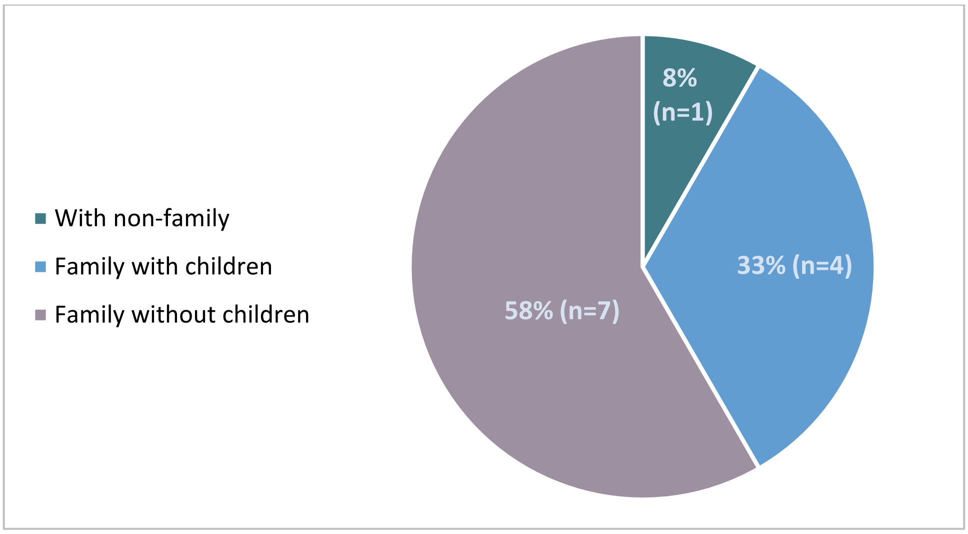

Figure 3.16: Living situation of respondents who evacuated multiple times during the 2016 Kaikōura earthquake tsunami (n=12).

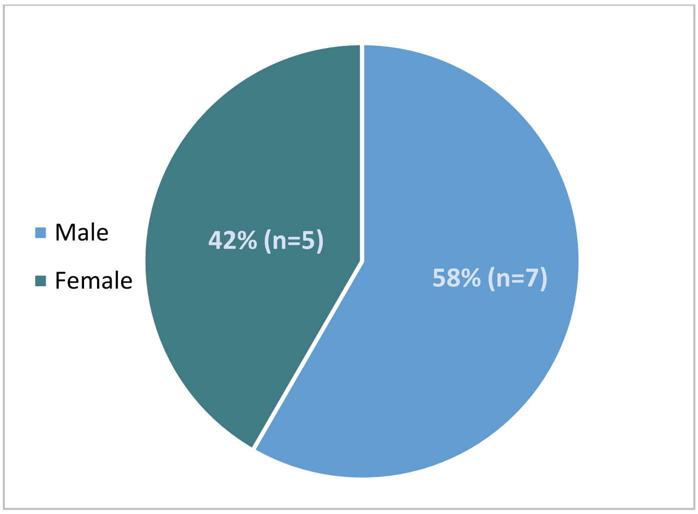

Figure 3.17: Gender of survey respondents who evacuated multiple times during the 2016 Kaikōura earthquake tsunami (n=12).

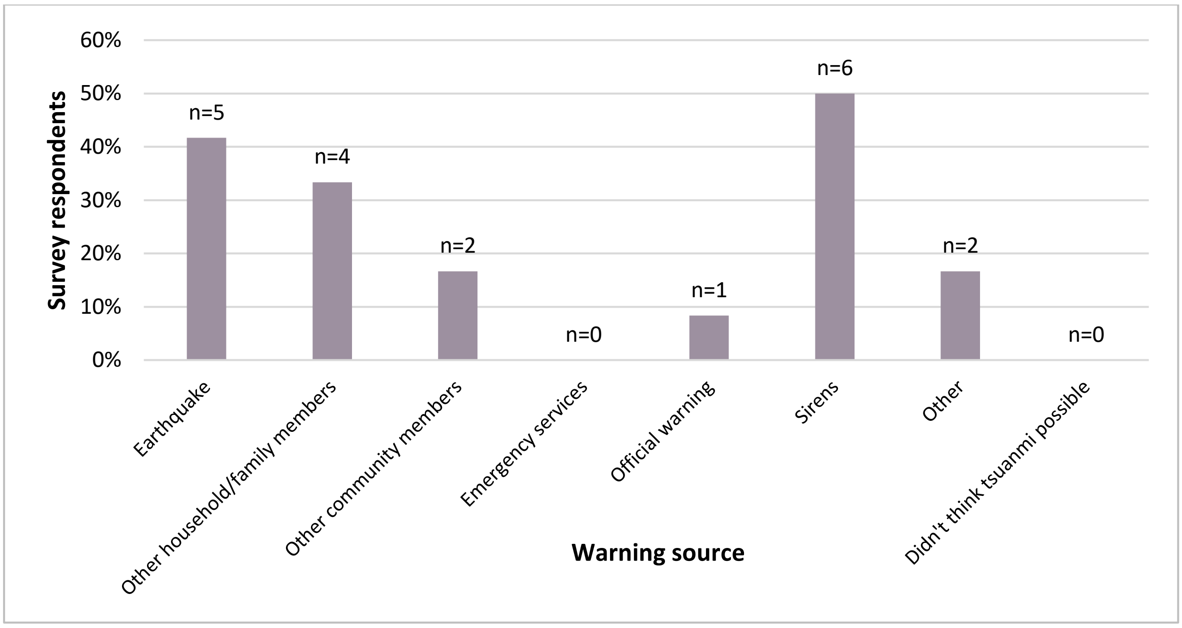

Figure 3.18: Warning sources recognised by those who evacuated multiple times (n=12). Note – survey respondents could select multiple actions for this question.

3.3.2.4 Evacuation Dynamics

The earliest evacuation time was approximately 12:10 a.m., coinciding with evacuating immediately after the earthquake (Figure 3.19). The latest evacuation time was approximately 3:10 a.m. Twenty-one respondents explicitly stated that they evacuated after the tsunami sirens were activated. Many respondents (19%, n=27) could not remember the time at which they evacuated. Forty-percent (n=4) of Banks Peninsula respondents evacuated at 12:30 a.m., with 21 (n=22) of respondents from Christchurch also evacuating at this time (Figure 3.19).

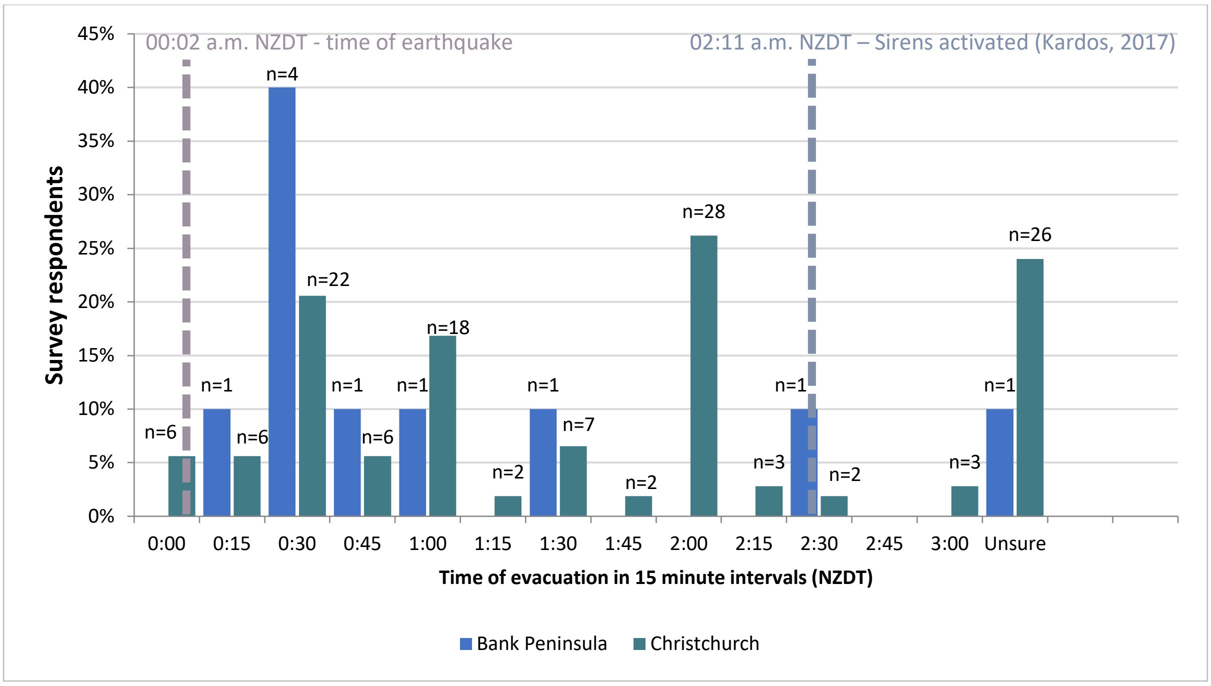

Figure 3.19: Time of evacuation shown by the percentage of survey respondents who evacuated during that 15 minute interval (n=114). A line has been added to show the approximate time the sirens were activated and the time of the earthquake.

The fastest evacuation journey took two minutes, while the longest took 120 minutes. The average journey took 22.88 minutes. The quickest journeys in Banks Peninsula were in Le Bons Bay (3 minutes), Little Akaloa (5 minutes) and Akaroa, Teddington, and Okains Bay (all 5 minutes). The fastest evacuation journeys in Christchurch where evacuees reached their destination in five minutes or less originated from Sumner, Mt Pleasant, Redcliffs, and North Brighton.

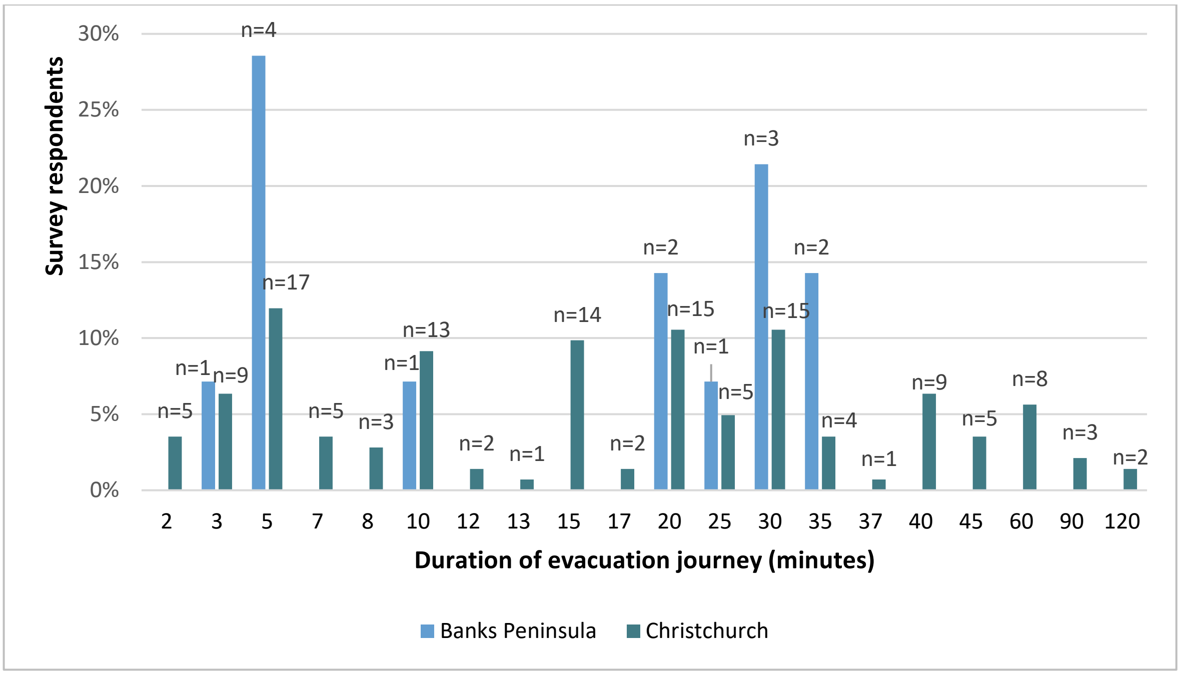

Figure 3.20: Duration of evacuation journey for respondents from Banks Peninsula and Christchurch in minutes (n=156). Note the scale on the x axis is not even, reflecting the evacuation journey durations provided by respondents.

The majority of the survey respondents reported that they evacuated by car (96%, n=156), with 2% (n=4) evacuating by foot. One person evacuated using a bicycle (1%). One other responded reporting using included using an electric scooter.

In all living situations the highest proportion of respondents evacuated by car (Figure 3.21). A similar percentage of respondents who reported that they lived either alone (1%, n=2), in a family with children (1%, n=1), or in a family without children (1%, n=1), identified that they evacuated on foot.

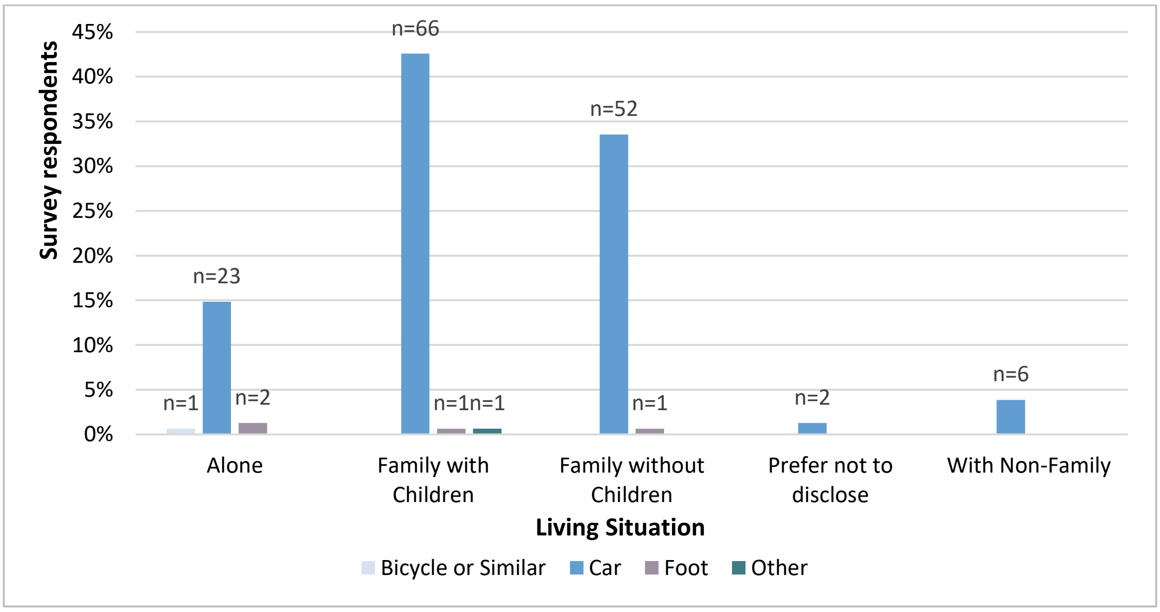

Figure 3.21: Percentage of people who evacuated by each transportation method shown for living situations (n=155).

Figure 3.22 shows the actions that were taken by respondents prior to evacuating in a car. Multiple action could be selected for this survey question. The most common actions taken were to gather household and family members (52%, n=79) and pets (38%, n=58). Other common actions taken included gathering life essentials (31%, n=48) and valuables (20%, n=30), while additional actions taken included getting blankets, bags, chargers, baby gear, and clothes.

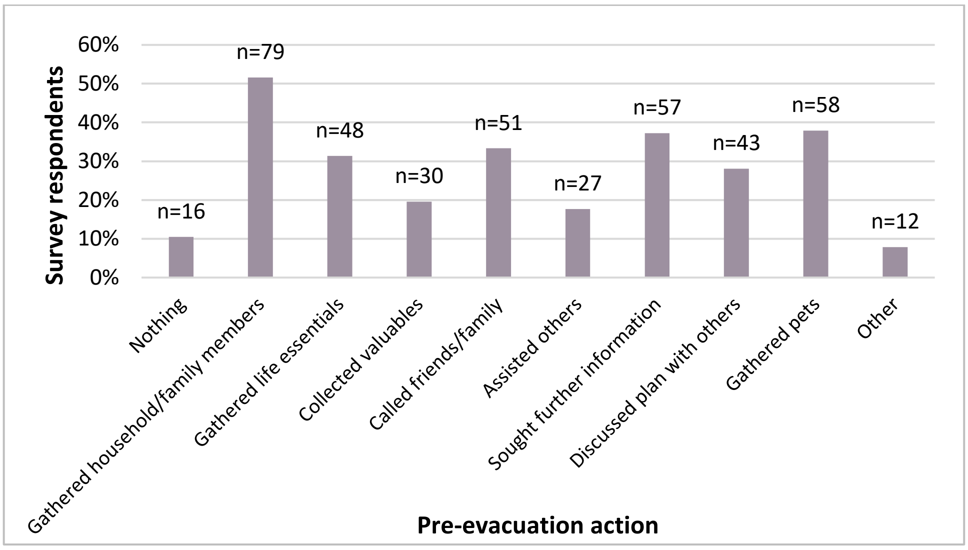

Figure 3.22: Pre-evacuation actions taken by respondents who reported evacuating by car (n=153). Note – survey respondents could select multiple actions.

Survey respondents were asked to record their origin, destination, and evacuation route. A total of 149 evacuation routes were documented. The evacuation routes can be viewed below in Figure 3.23, in which they have been divided up into the main study areas. There 13 evacuation routes from Banks Peninsula and 136 from Christchurch. One-hundred and five people evacuated from the orange evacuation zone, 30 from the yellow zone, while 14 people evacuated who were not in an evacuation zone. No one evacuated from the red evacuation zone (Table 3.11). The spatial distribution of evacuee's origin and destination points in relation to the tsunami evacuation zone can be seen in Figure 3.24. This shows that most coastal residents evacuated beyond the evacuation zone, while some evacuated into the yellow evacuation zone. For example, evacuees in Birdlings Flat reported evacuating to Christchurch or towards Akaroa, travelling further than the edge of the evacuation zone (near Poranui Beach Road and State Highway 75). A heat map of the origin (Figure 3.24) and destination points (Figure 3.26) can be seen below, showing the density of where evacuees left or relocated to. These maps show there was a high density of evacuees who left from the Sumner area, while also showing a high density of destination points around Sumner, and also Redcliffs and Mt Pleasant.

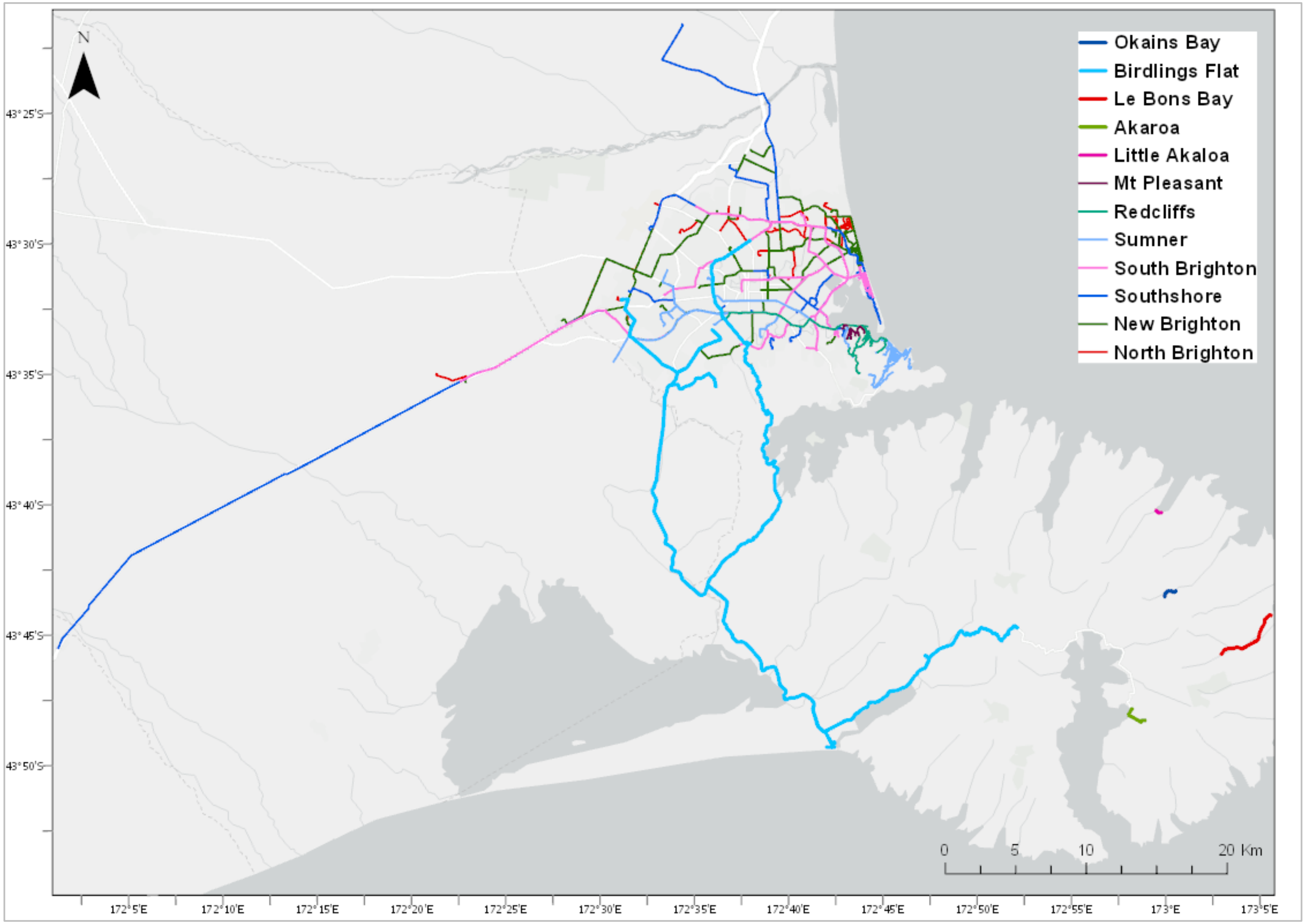

Figure 3.23: Evacuation routes documented by those from Christchurch and Banks Peninsula.

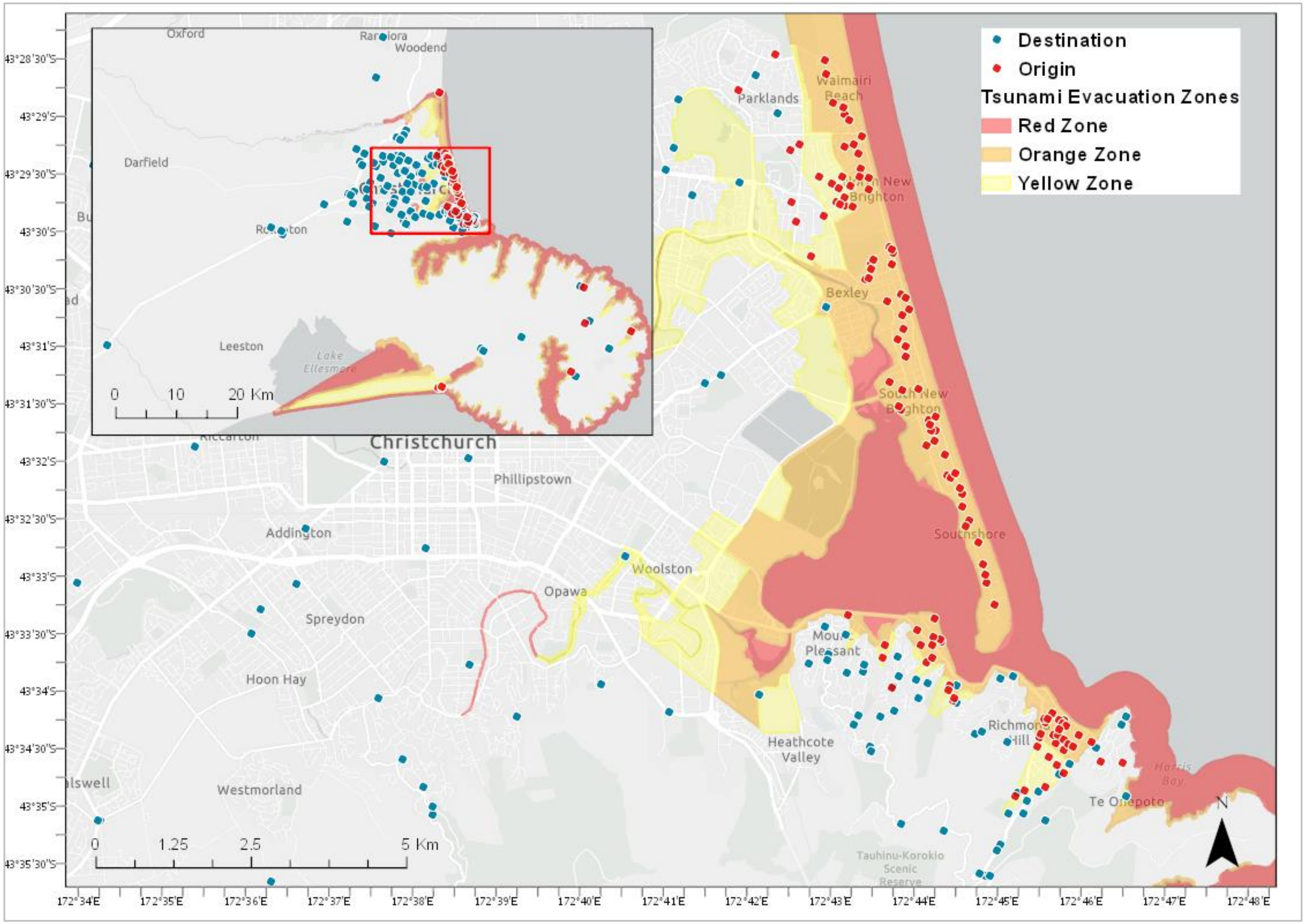

Figure 3.24: Spatial distribution of origin (red) and destination points (blue) of survey respondents during the 2016 Kaikōura earthquake tsunami evacuation. Note the evacuation zone in this map represents the zones at the time of the evacuation.

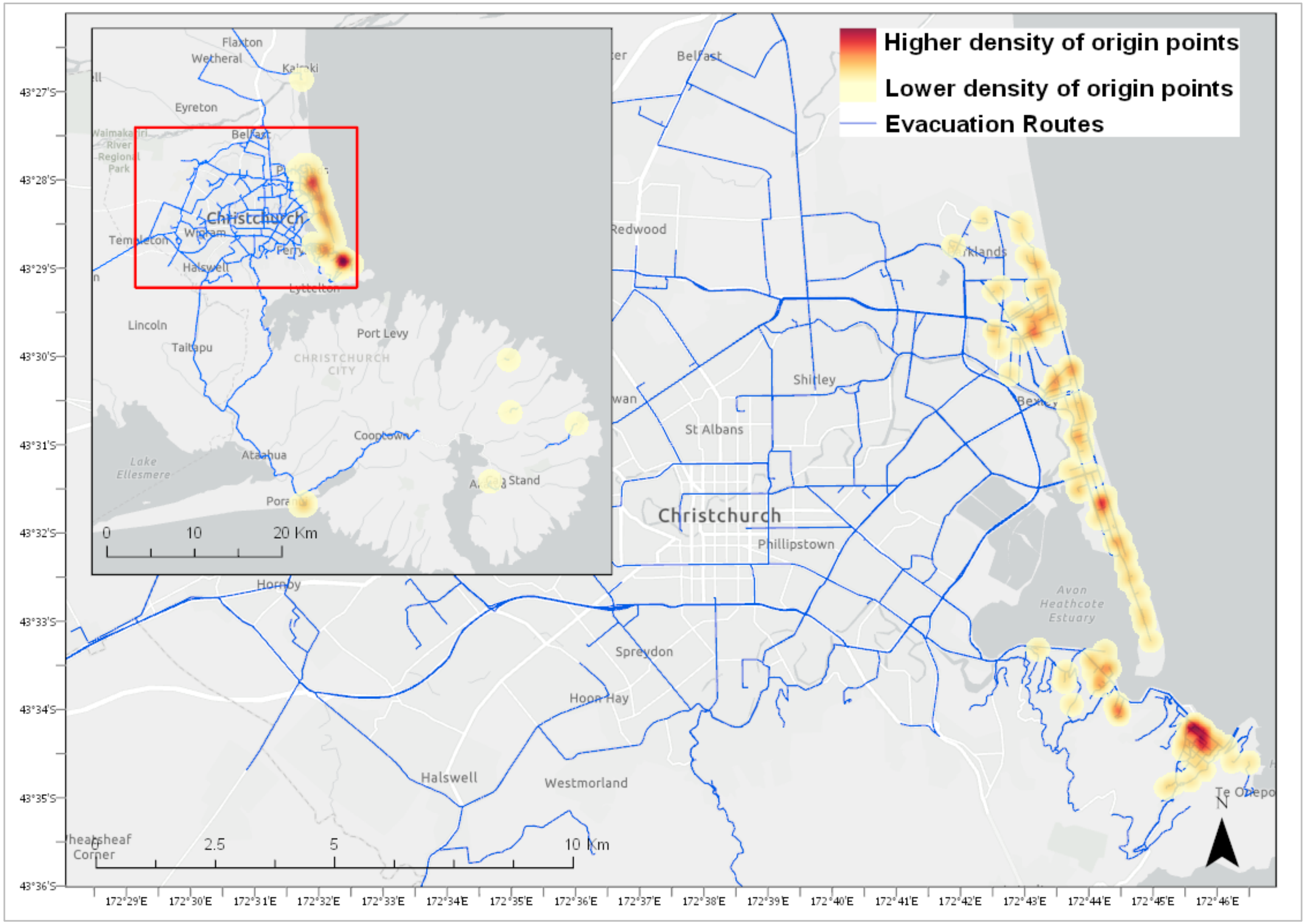

Figure 3.25: Heat map showing the origin locations of survey responses during the 2016 Kaikōura earthquake tsunami. Light yellow indicates areas where fewer respondents originated from, while darker red indicates areas where more respondents evacuated from.

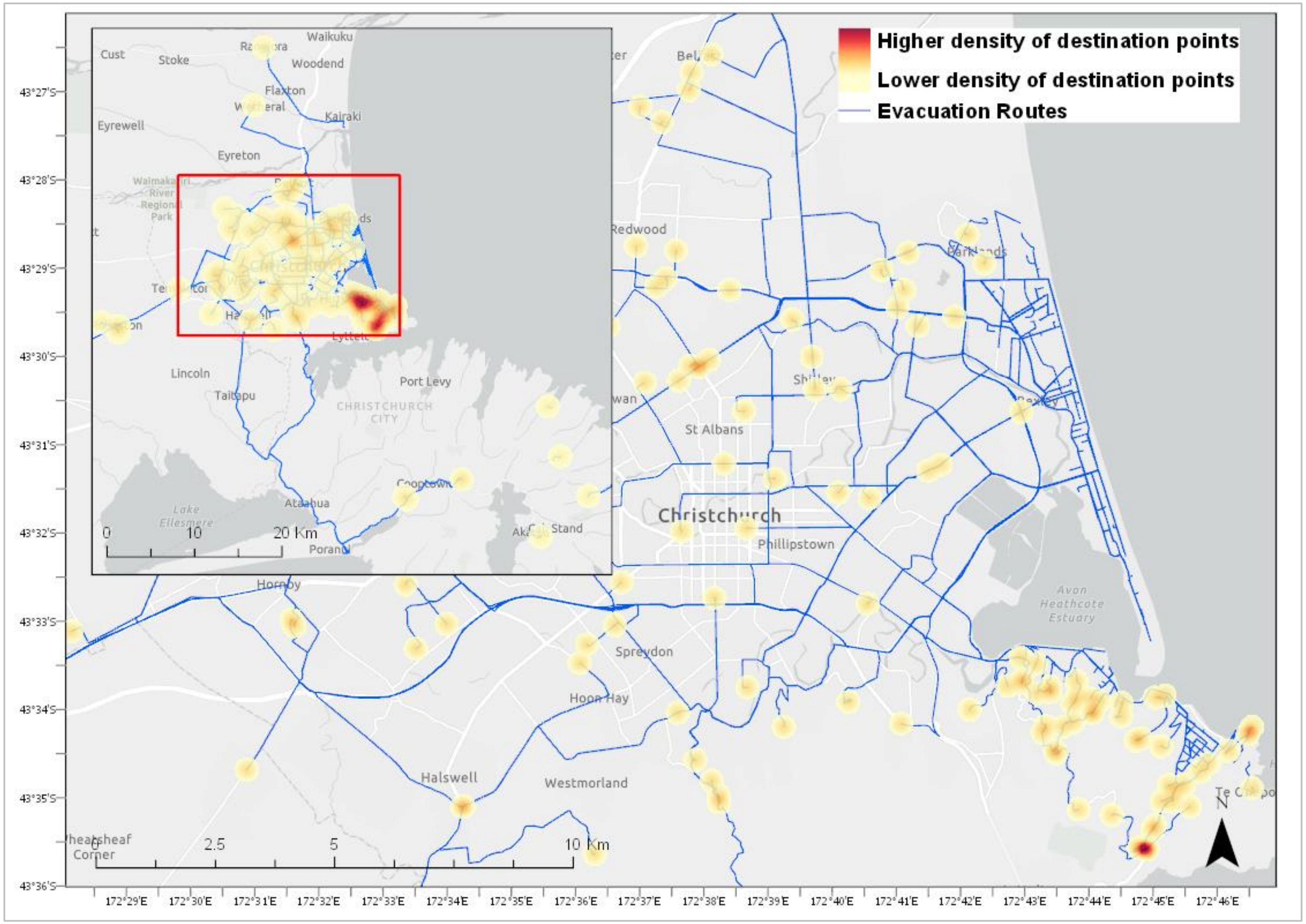

Figure 3.26: Heat map showing the destination locations of survey responses during the 2016 Kaikōura earthquake tsunami. Light yellow indicates areas where fewer respondents evacuated to, while darker red indicates areas where more respondents evacuated to.

Table 3.11: Percentage of respondents who evacuated from each evacuation zone.

Evacuation zone	Number who evacuated from zone	Percent
Red	0	0%
Orange	105	70%
Yellow	30	20%
Outside of evacuation zone	14	9%
Total	149	100%

Most people (62%, n=99) evacuated to the homes of friends or family, with a trend of horizontal evacuation across the greater Christchurch area (Figure 3.23, Table 3.12). Twenty-one percent (n=34) evacuated to higher ground and stayed on the side of the road (Table 3.12). Four percent (n=7) of respondents evacuated to other locations including Cowles Stadium, a church hall, and a lodge (commercial accommodation) (Table 3.12).

*Table 3.12: Location that survey respondents evacuated to**.*

Evacuation Location	Count	Percent
Home of friends/family	99	61%
School	4	2%
Mall	2	1%
Airport	2	1%
Civil Defence Centre	2	1%
Recreational Park	8	5%
Road	35	22%
Work	2	1%
Other	7	4%

**Note: Assumptions have been made when grouping the evacuation locations. These were based on the location of the respondent, local knowledge of the areas and specific evacuation routes. The locations include respondents who evacuated and provided an evacuation route, as well as respondents who reported they evacuated but did not provide enough details to produce an evacuation route (provided an evacuation destination/location, but did not provide an origin location).

Four percent (n=6) of the total survey respondents required assistance during the evacuation process. This included needing help to carry sick children and requiring transportation. Two survey respondents reported that they assisted others by providing to enable them to evacuate. A lack of transportation and mobility issues amongst elderly meant some respondents chose not to evacuate.

Congestion was observed by 41% (n=68) of the survey respondents. In Christchurch congestion was reported by one person from Mt Pleasant, 20 people in New Brighton, 15 from North Brighton, two from Redcliffs, eight from South Brighton, three from Southshore, 13 from Sumner, and five respondents from other communities that were not the focus of this research. Roads that were frequently mentioned to be congested included Evans Pass Road (n=8), Wakefield Avenue (n=4), Keyes Road (n=5), Bridge Street (n=14), Pages Road (n=6), Bowhill Road (n=6), Travis Road (n=6), and Estuary Road (n=6). Sixty-five congestion routes were documented, displayed below in Figure 3.27. Although congestion was observed during the entire evacuation process, it was most frequent between 12:30 a.m. to 2:30 a.m. The average speed of the traffic flow in areas that were congested was an estimated 28.1 km/hr. One respondent from Birdlings Flat (Banks Peninsula) observed congestion on State Highway 75 heading out of Banks Peninsula towards Christchurch.

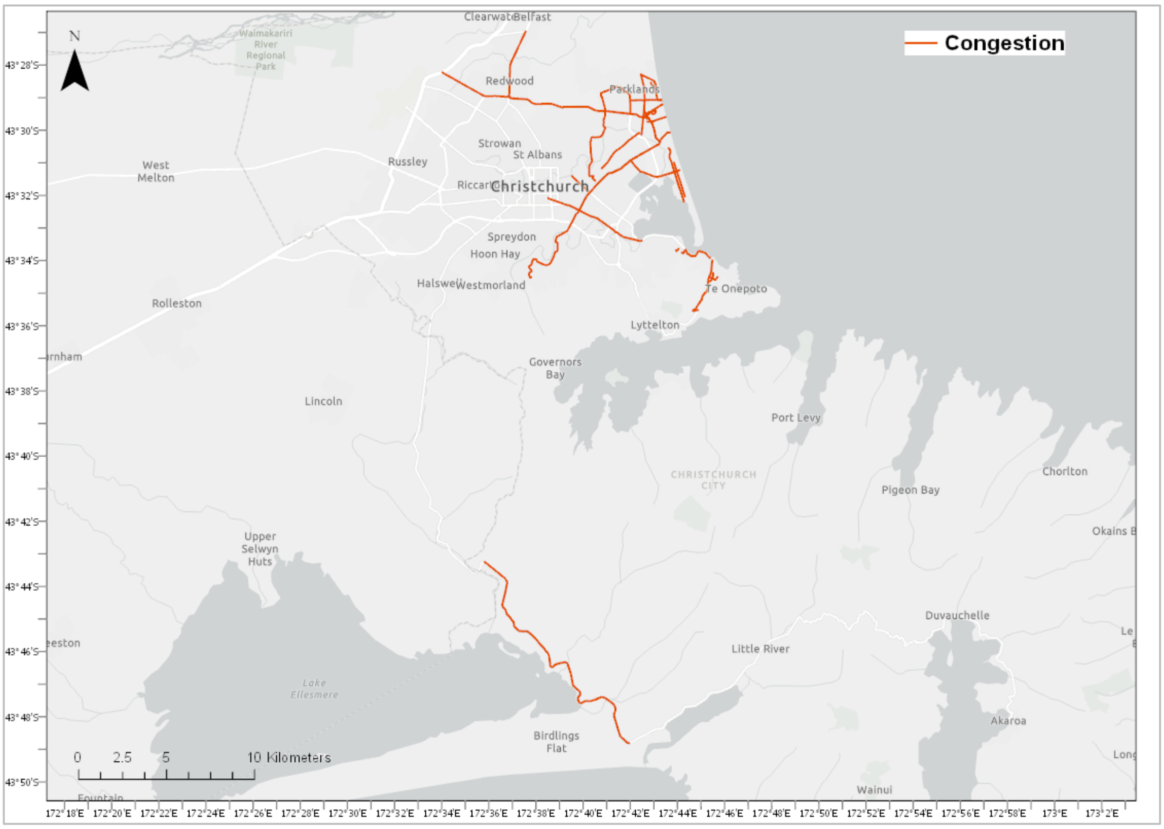

Figure 3.27: Congestion documented by those from Christchurch and Banks Peninsula.

The shortest time that was spent at an evacuation point was reported as 0.25 hours, while the longest reported time was for several days. The average time which respondents evacuated for was 5.93 hours. The average time spent at evacuation points was similar for Christchurch (5.98 hours) and Banks Peninsula (5.42).

Survey respondents were asked to select all the reasons that informed their decision to return home from their evacuation point. The most common reasons were that people felt it was safe and saw no evidence of danger (41%, n=64) or had received an all clear message from officials (39%, n=62). Thirty-nine percent returned home after discussing it with others (n=33) or after a reasonable time (n=29), while a further 30% (n=48) gave other reasons including the deactivation of the tsunami sirens, evidence of roads being re-opened or work and school commitments.

3.3.3 Preparedness, Risk Perception & Tsunami Knowledge

This section outlines the changes in knowledge and preparedness of tsunami risk before and after the 2016 Kaikōura earthquake. Information sources that were used during the evacuation process are also outlined.

Prior to this event, only 44% (n=82) of all survey respondents had discussed their evacuation plan with others. This percentage of respondents who undertook this preparedness action increased to 53% (n=100) following the 2016 earthquake. Similar increases were observed in other preparedness actions, including preparing a go-bag and an emergency kit. The percentage of respondents from Banks Peninsula who identified that they had discussed their evacuation plan decreased following this evacuation (Figure 3.28). Prior to the evacuation, two respondents from Birdlings Flat and one each from Akaroa and Le Bons Bay identified that they had discussed their evacuation plan, however did not answer that they had done this action after the 2016 event. Contrasting this, one respondent from each of Akaroa, Le Bons Bay, and Birdlings Flat who had not done this preparedness action prior to the evacuation, reported that they have since improved their resilience by discussing an evacuation plan with family members.

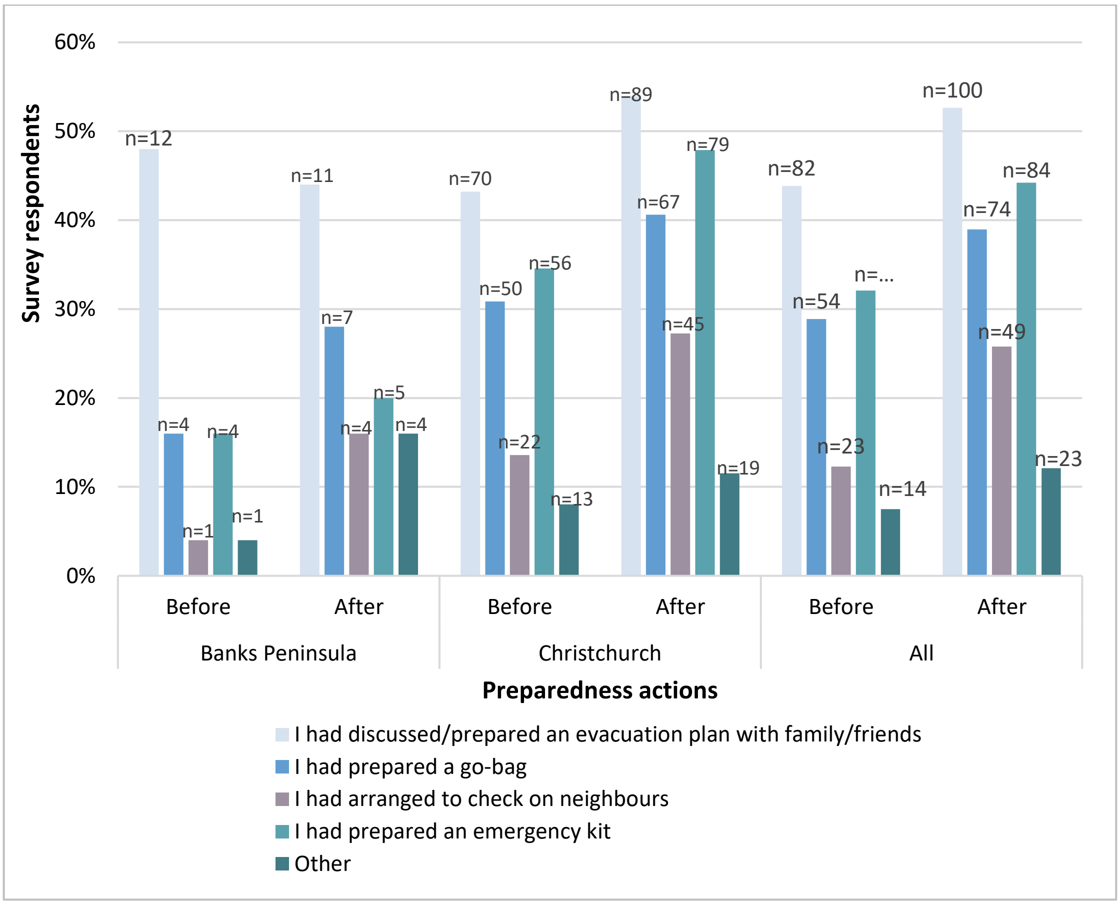

Figure 3.28: Change in tsunami preparedness actions for respondents before and after the 2016 Kaikōura earthquake tsunami. Data has been broken up to show Banks Peninsula and Christchurch results individually. The compiled data for all respondents is also included

Following the 2016 evacuation 48% of the total survey respondents have identified evacuation routes and destinations (n=91). Twenty-three percent of the total respondents also reported that they have since made themselves aware of tsunami evacuation zone information (n=44).

Survey respondents' level of knowledge of tsunami hazards and the need to evacuate appeared to increase following the 2016 Kaikōura earthquake (Figure 3.29). Prior to the tsunami evacuation in 2016, 18% (n=32) of the total respondents felt that their knowledge was non-existent to poor. This decreased to 6% (n=10) after the event. Contrasting this, while 38% (n=117) of the total respondents felt that their knowledge was good or very good before the evacuation, this increased to 82% (n=156) after this event.

The percentage of respondents from Banks Peninsula who felt that their knowledge was non-existent, and those from Christchurch who felt their knowledge was very poor, decreased from 4% (n=1) and 4% (n=2) respectively, to 0% (n=2) following the 2016 evacuation (Figure 3.29). In Banks Peninsula the percentage of those who felt their knowledge was very poor remained at 4% (n=1) both before and after the 2016 Kaikōura tsunami (Figure 3.29).

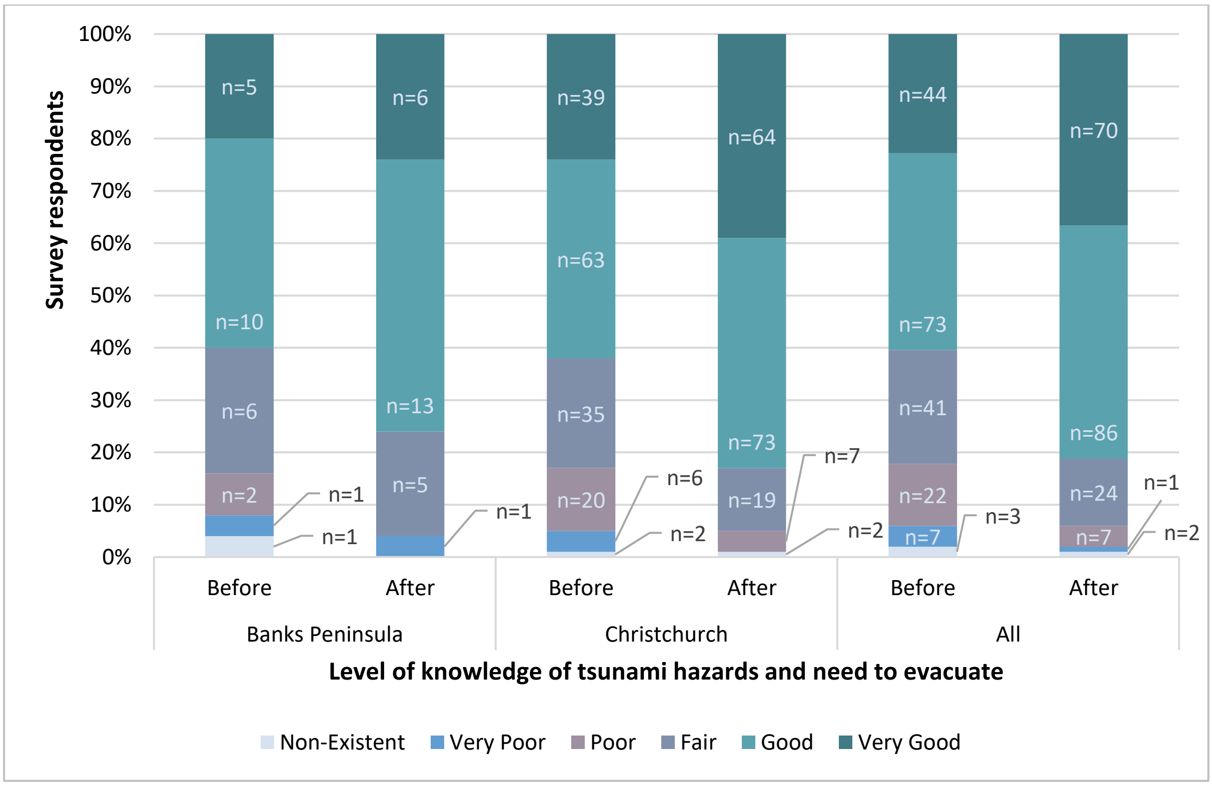

Figure 3.29: Change in level of knowledge of tsunami hazards and the need to evacuate before and after the 2016 Kaikōura earthquake tsunami. Data has been broken up to show Banks Peninsula and Christchurch results individually, with all compiled survey data also included.

The most commonly recognised information source from respondents was the use of media coverage of previous tsunami events, which was recognised by 60% of respondents (n=122) (Figure 3.30). Information from Civil Defence was recognised by a total of 45% of respondents (92). Other information sources included discussion with friends and family (46%, n=93), books and articles (35%, n=75), documentaries (34%, n=69), and Civil Defence public education sessions (26%, n=54). Discussions with Civil Defence staff (9%, n=19) and education from secondary school (9%, n=18) were the least recognised information sources. Only 3% (n=7) of the total respondents reported that they were not aware of tsunami hazards. As evident in Figure 3.30, the media coverage was the most recognised information source for residents of Banks Peninsula (67%, n=16) and Christchurch (59%, n=106). While secondary school education was the least recognised information source from Christchurch residents at 7% (n=12), tertiary education was the least recognised source in Banks Peninsula at 8% (n=2).

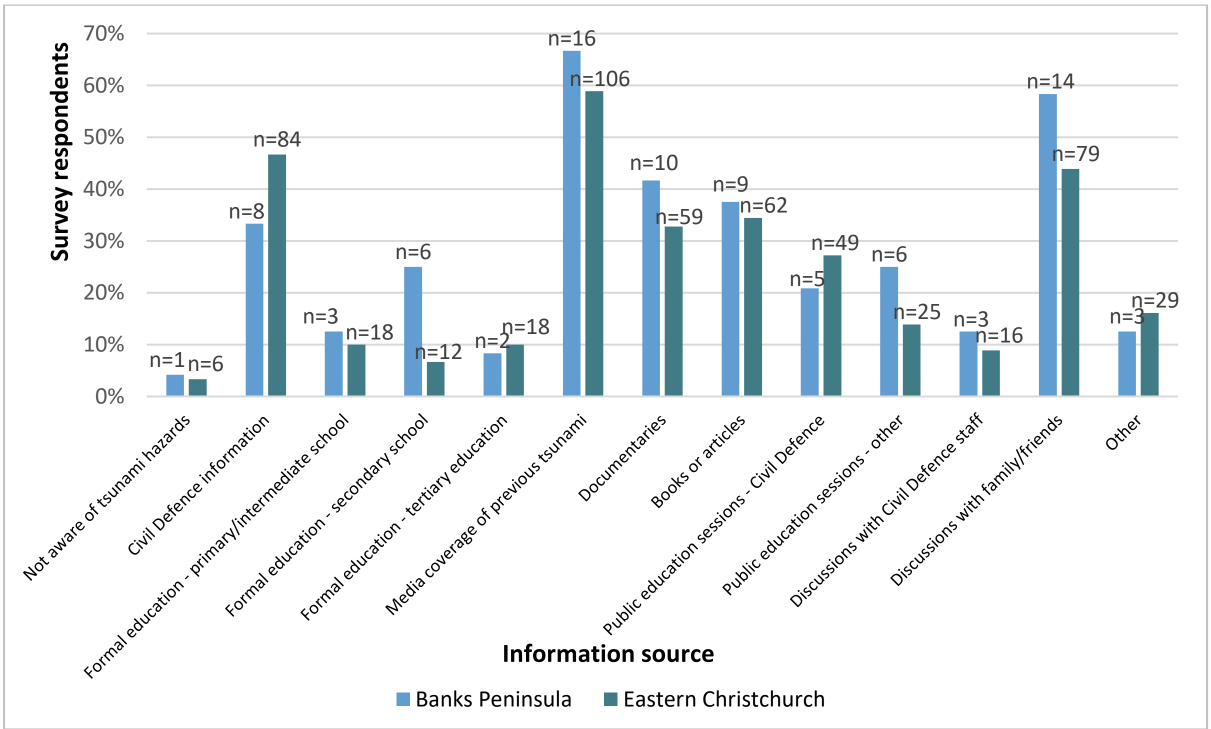

Figure 3.30: Information sources used by respondents that informed them on the need to evacuate.

The percentage of respondents from Banks Peninsula who felt that their knowledge was non-existent, and those from Christchurch who felt their knowledge was very poor, decreased to 0% following the 2016 evacuation. In Banks Peninsula the percentage of those who felt their knowledge was very poor remained at 4% (n=1) both before and after the 2016 Kaikōura tsunami.

3.4 Discussion

This section presents a discussion of some of the key themes and issues that were reported on in the tsunami evacuation survey. Where applicable, comparisons will be made to local and international literature. At the end of this section, limitations of this analysis, recommendations and future work are presented.

3.4.1 Warning Sources

Many tsunami evacuation behaviour studies, both globally and nationally, have shown that while natural warnings are a recognised source of a tsunami, there is a reliance or expectation on receiving tsunami warnings from official sources such as tsunami sirens or messages over the radio, television, or social media (Blake et al., 2018; Couling, 2014; Currie et al., 2013; Fraser, et al., 2013; Fraser et al., 2012; Fraser et al., 2016; Gregg et al., 2007; Hall et al., 2017). This trend is also evident in this survey. While 38% (n=77) of the total survey respondents identified the earthquake shaking as a natural tsunami warning source, approximately 70% of respondents reported that they were warned by official sources, including messages from Civil Defence over radio, television, or social media (34%) and the tsunami sirens (41%). Only 16% (n=33) of respondents identified that they were warned of a tsunami by community members, while family and household members warned 14% of respondents (n=28). The reliance on tsunami sirens was particularly noted in Christchurch suburbs (Figure 3.5), where there are multiple tsunami sirens present along the coastline (Kardos, 2017).

In this response, people underestimated the shaking duration and intensity and did not perceive there to be a tsunami threat. The survey results show that while many respondents reported feeling the earthquake, only 38% (n=77) recognised it as a natural warning for a potential tsunami (Figure 3.6). Seventy-three percent (n=150) of the survey respondents who felt the earthquake perceived the shaking intensity to be moderate or less, with 19% (n=40) perceiving the intensity to be strong/powerful, while a further 6% (n=12) felt it as severe/violent (shown in Figure 3.2). Figure 2.30 which shows a range of light to moderate shaking, similar to the shaking intensities recorded in this survey questionnaire, which are lower than the shaking intensities shown in Figure 2.29 which shows a range of light to strong shaking in Christchurch and Banks Peninsula. Instrumentally, the earthquake shaking duration was recorded to be approximately 120 seconds (Shi et al., 2017); however, as evident in Figure 3.3, of those who gave an estimation of the perceived shaking duration, 77% (n=122) felt that it was 60 seconds or less, while only 23% (n=37) perceived the shaking to be more than 60 seconds. Survey respondents noted that they compared the earthquake shaking experienced during the 2016 Kaikōura earthquake to earthquakes they had previously experienced in the 2010-2011 Canterbury earthquake sequence. Quantitative and qualitative responses from the survey indicate respondents did not perceive that the shaking was strong or long enough to generate a tsunami that they needed to evacuate for. Direct quotes from survey respondents regarding this include "*I didn't feel there was a risk of tsunami as the Kaikōura quake felt a lot smaller and less violent*" and "*the quake was not as severe as the September 2010, February 2011, June 2011 and December 2011 quakes*". As people did not feel the shaking was long or strong enough to generate a tsunami, they did not immediately self-evacuate. This highlights that reactions to warnings are highly contextual, and is consistent with previous research showing that previous risk experience influences reactions and responses to tsunami warnings (Charnkol & Tanaboriboon, 2006; Walch, 2018).

This warning and subsequent evacuation occurred in a confused warning environment (Lane et al., 2020). While tsunami warning education within New Zealand emphasises self-evacuation following long or strong earthquake shaking (MCDEM, n.d.), many survey respondents did not perceive the earthquake shaking to be long or strong so did not evacuate. Further to this, as outlined in Section 2.4.1, the official warnings for the 2016 Kaikōura tsunami event that were released by authorities were contradictory, with information released from RNC and Christchurch Police informing people to evacuate, while CCC CDEM did not believe there to be a tsunami threat (Kardos, 2017. This was noted by respondents who felt that there were "*conflicting announcements on the radio"* with *"national radio saying there was a risk of tsunami and on local radio this was rebutted"* and "*the police and Civil Defence seemed to have different opinions on the need to evacuate"*. Adding to the confusion in the messages that were being released, data surrounding the magnitude and epicentre of the Kaikōura earthquake suggested that there was not a tsunami threat (Kardos, 2017; MCDEM, 2017b; Power et al., 2017). These factors meant that it took time for the tsunami threat to be fully identified, subsequently resulting in a delay in the release of official warnings and the evacuation of those in Christchurch and Banks Peninsula.

In addition to the reliance on official warnings, the confused warning environment in which this tsunami evacuation occurred meant that residents of Christchurch and Banks Peninsula did not behave as authorities had anticipated and intended. These residents did not interpret the earthquake shaking to be a natural tsunami warning source, and subsequently did not immediately self-evacuate. This behaviour was also observed in other areas of New Zealand during this evacuation (Blake et al., 2018). This issue prompted MCDEM to launch the multi-media *'Long and Strong, Get Gone'* campaign, which emphasised the importance of immediate evacuation from coastal locations following long and/or strong earthquake shaking (MCDEM, 2017c). This campaign demonstrates a positive example of tsunami warning education and highlights the value of public education campaigns. In this survey, five respondents reported that following *the 'Long and Strong, Get Gone'* campaign, their evacuation decision would be different and they now would self-evacuate immediately. Further to this, in a nation-wide study of awareness of disasters, public awareness of either moving inland or to higher ground, or recognition of the *'Long or Strong, Get Gone'* phrase increased from 83% in 2017, to 90% in 2018 (MCDEM, 2018b).

3.4.1.1 Warning Sources & Multiple Evacuation

Identified in the evacuation process, Makinoshima et al. (2020) noted that evacuees can engage in an extra step in the evacuation process known as additional evacuation. The authors stated that this step consists of re-evacuating after the initial evacuation, and for evacuees the decision is made based on an ongoing risk assessment or the need to return home to gather items. Reported in Section 3.3.2.3, during the 2016 Kaikōura earthquake tsunami evacuation, twelve respondents (one from Banks Peninsula and 11 from eastern Christchurch) reported that they took part in an additional evacuation step. However, the reasoning behind was different to those reported by Makinoshima et al. (2020). During this evacuation, people were unaware of their risk and the need to evacuate due to the conflicting information being released by authorities. One group of survey respondents who evacuated twice evacuated immediately after the earthquake shaking but when the *"Civil Defence website said there was no risk"* they returned *"back into the possible inundation zone".* Following messages confirming the tsunami threat, this group of respondents re-evacuated. This factor has also been outlined by Lane et al. (2020). The second group of respondents evacuated after the activation of the tsunami sirens. As the sirens had been programmed to only sound every hour for 15 minutes (Kardos, 2017), people returned home once they thought the sirens had stopped; however, the sirens *"started again"* so people *"evacuated again"*. Fifty percent (n=6) of those who evacuated multiple times identified the tsunami sirens as a warning source for their evacuation decision, further demonstrating the influence of tsunami sirens during this evacuation (Figure 3.18). These examples are similar themes to what was reported by Blake et al. (2018) during the same evacuation, when 9% of respondents in Petone and Eastbourne (Wellington) evacuated did not see others evacuate, or returned home following absence of initial confirmation of the tsunami threat, but evacuated following the release of the official warning. These examples (both in this research and the example from Blake et al.'s research) suggest that tsunami warning education needs to include information on the use of official warnings and how people will know it is safe to return home.

3.4.2 Pre-Evacuation Actions

After perceiving there to be a tsunami threat, people often take preparatory actions (Makinoshima et al., 2020). Ninety-percent (n=151) of survey respondents from Bank Peninsula and Christchurch undertook some form of action before evacuating (shown in Figure 3.9). This included gathering life essentials (30%, n=51), contacting friends and family (32%, n=53), and discussing evacuation plans (27%, n=45). Partaking in these actions is consistent with actions taken during other tsunami evacuations, including the 2009 Samoa tsunami and the 2004 Indian Ocean tsunami (Couling 2014; Lindell et al., 2015; Løvholt et al., 2014). It has been reported in other tsunami evacuations (including the 2009 Samoa tsunami, 2011 Tōhoku tsunami, and the 2018 Sulawesi tsunami) that often people prepare to evacuate once they have perceived there to be a tsunami threat (Makinoshima et al., 2020). This trend was evident in survey data from the 2016 Kaikōura tsunami evacuation, shown by respondents reporting that they gathered life essentials (30%, n=51) and collected valuables (18%, n=31) once they were aware of a tsunami threat. These actions lead to a delayed evacuation, and increase the risk to evacuees who subsequently spend more time in the exposed coastal locations.

Only 10% (n=17) of the total survey respondents reported that they evacuated immediately and did not participate in any pre-evacuation actions. As shown in Figure 3.10, the highest proportion of those who evacuated immediately lived as a family (47%, n=8). It is worth noting that a total of four of these respondents also reported that they had gathered their pets, family members, and/or sought further information, suggesting that they considered this to be a part of their immediate evacuation process.

One of the most common actions evacuees of Banks Peninsula and Christchurch took part in was seeking further official information to inform evacuation decisions. Thirty-nine percent (n=66) of the total survey respondents sought further information from Geonet, Radio NZ, and local and national Civil Defence (through the radio, websites including Facebook and Twitter, and the television) prior to evacuating (Figure 3.9). The action of seeking further information is consistent with Step 2 of Perry and Green's process of forming protective behaviour (1982), as well as Makinoshima et al. evacuation process (2020). This action has been observed in other evacuations (including Lindell et al., 2015) and is recognised as a common activity people partake in prior to forming an evacuation decision (Makinoshima et al., 2020). In the 2016 Kaikōura evacuation, survey respondent's participation in seeking further information can potentially be linked to two factors. Firstly, the lack of recent tsunami events contributed to a low risk perception towards respondent's personal risk and the need to evacuate. A contributing factor to this was likely that survey respondents did not recognise tsunami to be an issue following an earthquake. Previous experiences during the 2010-2011 Canterbury earthquake sequences saw false evacuations, with reports of 21% of coastal residents in Christchurch evacuating during the 2010 earthquake upon the strong/long earthquake shaking, only to find there was no tsunami threat (Dorfstaetter in Fraser et al., 2013), likely influencing future belief of a tsunami threat following an earthquake. Secondly, the warnings that were being received were confusing (see Sections 2.4.1 and 3.4.1). This meant it was difficult for people to make an evacuation decision, so sought further official information to help inform their decision. It was not until an official evacuation warning was released from MCDEM and CCC CDEM that people chose to evacuate. The "*differing opinions on the need to evacuate and breakdown in communication*" from authorities during this response led to a decrease in trust from the public in these authorities. It has been recognised that consistent credible warnings can increase trust from the public in those providing the warning, whilst influencing an efficient prompt evacuation (Potter et al., 2018). It is therefore crucial that in future evacuations all authorities involved share consistent messages to the public, thereby allowing people to make informed evacuation decisions and efficiently evacuate.

3.4.3 Evacuation Dynamics

Seventy-three percent (n=161) of survey respondents evacuated at some stage after the Kaikōura earthquake (Section 3.3.2.2). The evacuation rate recorded in this Masters research is similar to the 70% of people who reported evacuating from Petone and Eastbourne, Wellington, New Zealand, during the same event (Blake et al., 2018), while it was reported that 69% of survey respondents from Kaikōura evacuated during this event (Tilley, 2020). The evacuation rate in Kaikōura was attributed to extensive efforts made by the local CDEM group in educating the community on tsunami evacuation warnings and evacuating, while the majority of those who did not evacuate from the survey sample reported that they were not inside a tsunami evacuation zone so had low risk perception towards the need to evacuate (Tilley, 2020). In Hokkaido during the 2003 earthquake tsunami, a survey revealed the evacuation rate was 55.8%, with factors including feeling in danger and being close to higher grounds influencing the decision to evacuate (Hiroi et al., in Makinoshima et al., 2020). In 2006 and 2007 large earthquake events saw the JMA issue tsunami warnings for coastal cities including Hokkaido. The evacuation rate decreased from 46.7% in 2006 to 31.8% in 2007, with the decrease largely due to evacuating for a small event in 2006 (Yoshii et al., in Makinoshima et al., 2020). In a survey of Donggala Regency and Palu City (Indonesia) it was found that only one respondent did not evacuate to reduce their tsunami risk during the 2018 Sulawesi tsunami, however this respondent was out of the tsunami risk area. Reasons for evacuating for other evacuees included the ground shaking, but predominately from observing others evacuate (Harnantyariet al., 2020). Goto et al. (2013) investigated the evacuation rate in Banda Aceh following the 2012 Sumatra earthquake tsunami and found that approximately 90% of survey respondents in the coastal zone evacuated, while this decreased to between 54-73% of residents who were inland at the time of the evacuation.

The evacuation rate of survey respondents from Banks Peninsula and Christchurch can be attributed to three factors. Firstly, 59% (n=122) of respondents felt that the shaking was 60 seconds or less (shown in Figure 3.3), while 73% (n=150) percent felt that the shaking was of moderate intensity or less (MMI 5 or lower, see Section 3.3.1.1). Consequently, survey respondents' perception of the shaking intensity and duration lowered their risk perception during this event. In comparison, during the 2011 Tōhoku earthquake tsunami, there was a much higher evacuation rate, with officials estimating the earthquake shaking to have lasted up to three minutes, while also perceiving the shaking intensity to be stronger or unusual to previous earthquake experiences, thereby increasing their risk perception (Fraser et al., 2012). It has been recognised that experience with disasters can increase risk perception and positive behaviour during future events as people have prior experience of the risk so they can easily imagine the impacts (Dash & Gladwin, 2007; Dzialek, 2013). For example, in a region-wide survey of Tōhoku following the 2011 earthquake tsunami, it was reported that 21.5% did not evacuate as they had not previously experienced a severe tsunami, so had less information and experience to inform their evacuation decision (Cabinet Office in Japan in Makinoshima et al., 2020). There have been very few tsunami evacuations within New Zealand, including in Banks Peninsula and Christchurch, where the last major evacuation was in 1960 (Johnston et al., 2008). Therefore, respondents in Christchurch and Banks Peninsula have had fewer experiences with tsunamigenic earthquakes, lowering their risk perception towards the 2016 tsunami. There were some exceptions to this, including a survey respondent who had experienced the 2009 Samoa tsunami who reported they are *"highly sensitive to this sort of natural hazard".* Finally, it has been recognised that false alarms and warnings, and evacuating for small or non-existent tsunami threats can lower tsunami risk perception (Tobin et al., 2013). As explained above, previous evacuations in Hokkaido for small tsunami waves led to people not perceiving there to be a tsunami threat and consequently not evacuating (Yoshii et al., in Makinoshima et al., 2020). This is likely to have occurred in this evacuation. As mentioned in Section 3.4.2, during the 2010 and 2011 Canterbury earthquake sequence, it was reported that people evacuated inland or to higher ground after experiencing strong earthquake shaking, only to find out there was no tsunami threat (Dorfstaetter in Fraser et al., 2013). This would have influenced people's evacuation decisions during this event. These factors led to survey respondents of Banks Peninsula and Christchurch having a lower tsunami risk perception towards the earthquake shaking and the need to evacuate, with many respondents evacuation decisions based on the release of official tsunami warnings (as explained in Section 3.4.1).

3.4.3.1 Evacuation & Perceived Earthquake Shaking

It is advised that if coastal residents experience earthquake shaking that is strong or of a duration of 60 seconds or more, they should immediately self-evacuate. This is a recognised action to reduce risk for regional source tsunami by authorities including CCC CDEM, Canterbury CDEM and ECan (Jack & Schoenfeld, 2017; MCDEM, n.d.; MCDEM, 2018) to reduce exposure for a regional source tsunami. The instrumental earthquake shaking recorded for the 2016 Kaikōura earthquake was 121 seconds (Shi et al., 2017). Advice from ECan, who have developed tsunami evacuation zones for Christchurch in collaboration with other local authorities including CCC, states that coastal residents of Christchurch and Banks Peninsula should evacuate following long earthquake shaking of more than 60 seconds (Jack Schoenfeld, 2017). Following this advice, it would be hoped that people would evacuate if they perceived the shaking to be more than 60 seconds in duration, along with strong in intensity. The perceived earthquake shaking intensity and duration was plotted against the evacuation rate for each shaking intensity duration, shown in Figure 3.15. Despite authorities' recommendations to evacuate following earthquake shaking of 60 seconds or more, Figure 3.15 shows that not all respondents who perceived the shaking duration to be this long evacuated. For example, 82% (n=9) of the respondents who perceived the earthquake shaking to be 80-100 seconds evacuated, while this decreased to 60% (n=3) for the respondents who perceived the shaking to be more than 121 seconds. Of those who did not evacuate, yet perceived the shaking to be more than 60 seconds, six were not in the tsunami evacuation zones during this event, while two reported that their knowledge of the epicentre of the earthquake, along with the initial statement released that there was no tsunami threat influenced their evacuation decision. Most of the respondents who felt that the earthquake shaking was of long duration but did not evacuate perceived the shaking to be moderate (n=10), while one respondent felt that it was gentle and a further respondent felt that it was violent/severe. A total of fifty-six percent (n=87) of respondents who perceived the shaking intensity to be 60 seconds or less evacuated during this tsunami event. Forty-six percent (n=73) of these respondents felt that the shaking was of a moderate intensity, while 17% (n=26) felt that it was violent/severe.

Despite so many evacuating because of the tsunami threat (Section 3.3.2.2), data indicates that while some respondents (31%, n=34) likely evacuated due to the natural warning, many of those who evacuated did so for other reasons. One potential reason is the official warnings. As previously explained, there was a reliance on using official warnings to recognise the tsunami threat during this evacuation. Although people did not perceive the shaking to be over the threshold prompting self-evacuation, once they had received confirmation of the tsunami threat from officials – either over the radio or social media, or through the activation of the tsunami sirens – they evacuated. This further exemplifies the reliance on official warnings to prompt evacuations during this event, highlighting the importance on educating the public on natural tsunami warnings.

3.4.3.2 Evacuation & Living Situation

Literature on evacuation behaviour shows that household composition can be influential in evacuation decisions. Studies have reported that living with children was more likely to encourage positive evacuation behaviour (Dash and Gladwin, 2007; Hasan et al., 2011; Tobin et al., 2013). This is because parents and caregivers aim to protect children, and during a tsunami evacuation can do so by evacuating to a safer location (Tobin et al., 2013). The data recorded from Christchurch and Banks Peninsula is consistent with these studies, with Figure 3.13 showing that the highest percentage of evacuees identified as living as a family with children (45%, n=62). Supporting this claim, Figure 3.14 shows that 78% (n=62) of the survey respondents who were living in a family with children evacuated, with only 22% (n=17) choosing not to evacuate. A general statement can also be made from these results that living in a family of any type – with or without children – was more likely to result in positive evacuation behaviour. Thirty-four percent (n=46) of the total evacuees were people who lived in a family without children, bringing the total of evacuees living in a family of any type to 78% (n=108) (Figure 3.13).

3.4.3.3 Evacuee Origins

As outlined in Section 2.3.2.3, three tsunami evacuation zones have been utilized in Christchurch and Banks Peninsula. In using three evacuation zones, it is hoped that there will not be evacuations larger than what is necessary, as this can reduce risk perception towards future evacuations (MCDEM, 2016). Based on the guidelines surrounding the use and development of the evacuation zones in Christchurch and Banks Peninsula, as the 2016 the Kaikōura earthquake generated a regional source tsunami, only those in the red and orange evacuation zones were required to evacuate (Jack & Schoenfeld, 2017). While 70% (n=105) of respondents who evacuated were in the orange tsunami evacuation zone at the time of this event, it was noted that 30% were in either the yellow zone (n=30) or were outside of the tsunami evacuation zones (n=14) (see Table 3.11). Survey respondents commented that there were "*too many people on the road"* and that people evacuated "*who didn't need to".* A contributing factor in this issue is that while tsunami evacuation zone maps were available on CCC CDEM's website during the 2016 earthquake and tsunami, many people were unaware of the maps and were not directly linked to them during the event (Kardos, 2017). People were also generally unaware of the extent of the tsunami evaucation zones during the event (Lane et al., 2020). For example, a survey respondent commented that during this evaucation they "*not in the evacuation zone, but chose to leave as we didn't know that at the time"*. This highlights that during this tsunami evacuation people were unaware of their tsunami risk and did not know what to do, with many taking a safe appraoch by evacuating regardless. People lacked education on the tsunami evaucation zones and how this relates to tsunami warnings. As stated, a reason for implementing three evacuation zones is to ensure that people do not need to evacuate unnecessarily (MCDEM, 2016), as this can decrease trust in authorities and risk perception towards future tsunami evacuations (Doyle et al., 2014; Tobin et al., 2013). It is therefore crucial that community members of Banks Peninsula and Christchurch are educated on the tsuanmi evaucation zones, to ensure that in future evaucations they know their personal risk so can make an informed decision regrading their need to evaucate. Encouragingly, following this evacuation, 23% (n=44) of survey respondents have made themselves aware of their evacuation zone. An interactive evacuation zone map is also available online and can be accessed from both CCC CDEM (CCC, n.d.) and Canterbury CDEM (Canterbury Maps, n.d.). There has also been community engagement to present and explain changes in the evacuation zones to communities in Christchurch to help improve tsunami risk awareness (CCC, 2019).

3.4.3.4 Evacuation Locations

A high proportion (61%, n=99) of the total survey respondents provided an evacuation destination that suggested they evacuated to the homes of friends and family (Table 3.12). Within this, 16% (n=24) provided a destination that specifically said their relationship to the location in which they evacuated (including "*up the hill to a friend's place*"). Commitments to work and school were influential in five survey respondent's decisions to return home (see Section 3.4.3.5), so likely influenced people's decisions in where they evacuated. Because of school and work still occurring the day of the evacuation, people likely chose to evacuate to the homes of friends and family to ensure they could get some sleep before work. While people evacuated to friends and families homes in the Heathcote and Banks Peninsula Wards, people also evacuated to the side of the road, with 40% (n=22) and 38% (n=5) respectively evacuating to this location (Figure 3.31). This was likely because of their close proximity to higher ground, so could efficiently travel up nearby hills and wait on the side of the road for the evacuation to end. In suburbs of the Coastal Ward which are on flatter land and further from hills, 77% (n=55) of evacuation destinations were to the homes of friends and family (Figure 3.31). Three evacuation centres were opened during this evacuation (Kardos, 2017), however only 1% (n=1) of respondents from the Coastal Ward evacuated to these centres (Figure 3.31). A respondent from Banks Peninsula also travelled to an evacuation centre (8%, n=1). Five percent (n=4) of respondents from the Coastal Ward evacuated to schools (Figure 3.31), with one respondent stating that they made this decision as they "*didn't have friends or family to go to*" and knew the school their children went to was "*open with resources for evacuees*". One respondent from Mt Pleasant reported that while they did not evacuate their house, they did evacuate vertically to the upper level of their home – this respondent was not in an evacuation zone. Rather than evacuating themselves, two survey respondents from Teddington and Redcliffs who did not evacuate due to the initial absence of sirens and living on higher ground, reported that they had family or friends evacuate to their homes.

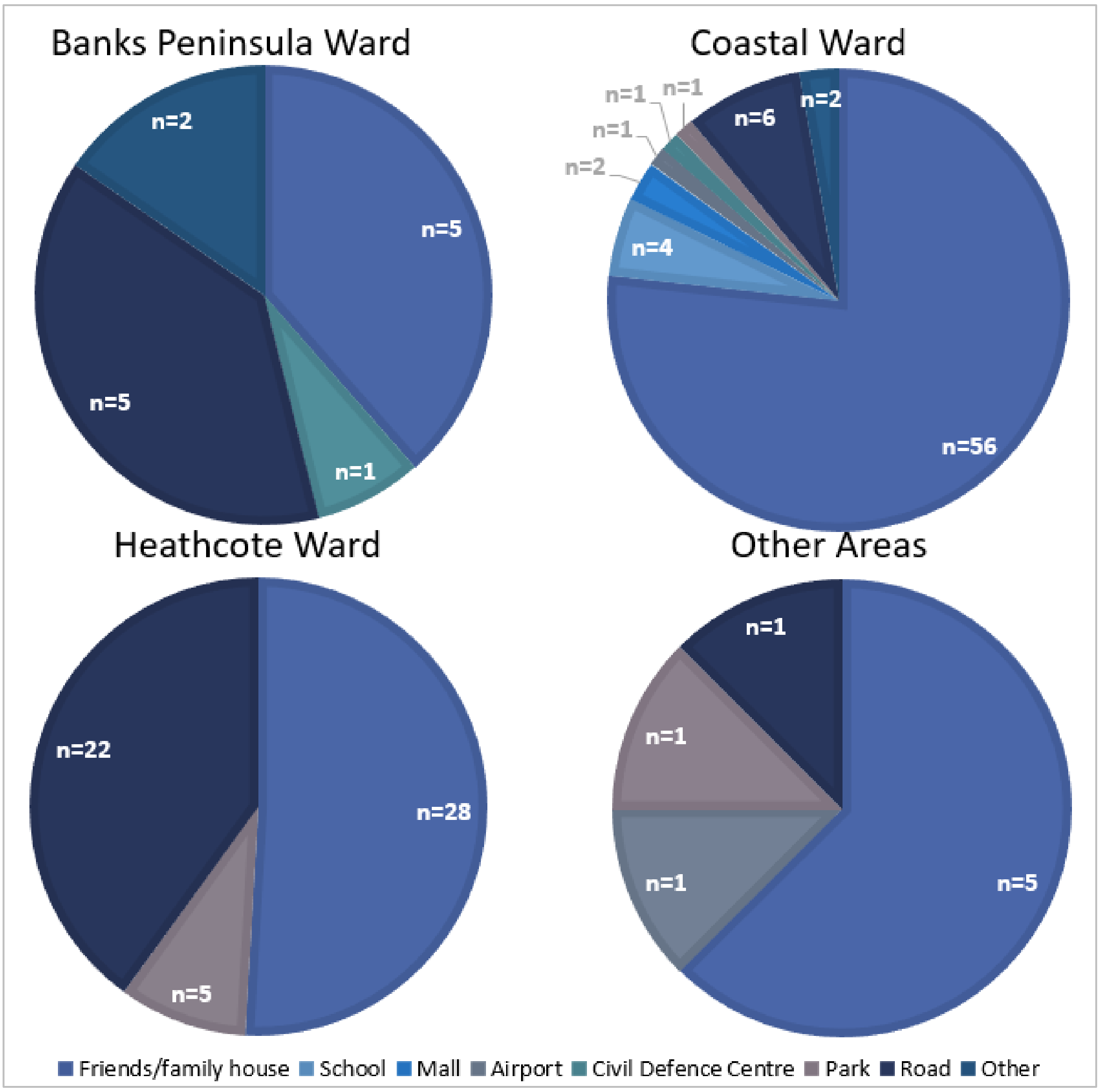

Figure 3.31: Locations respondents evacuated to for each ward (Banks Peninsula, Coastal and Heathcote) along with surveys received from areas which were not the focus of this study.

3.4.3.5 Return Home

The final stage of the evacuation process is the return home (MCDEM, 2008; Tobin et al., 2013). It has been recognised that this stage involves an assessment of the evacuated area, and that once the area has been identified as safe, an all-clear to return is given (MCDEM, 2008). Fraser et al. (2013) recognised that intended actions relating to when people return to an inundation zone need to be explored, with literature related to this aspect being scarce for empirical data of evacuations. Harnantyari et al. (2020) reported that following the 2018 Sulawesi tsunami evacuation, more than 50% of survey respondents did not feel safe to return home after a week or more, with the authors noting that this was not surprising given the event.

To provide a comprehensive overview of the evacuation process, a question relating to the time spent at an evacuation point and influencing factors in the return home was included in the questionnaire survey for this research. In the 2016 Kaikōura tsunami evacuation, respondents from Christchurch and Banks Peninsula spent between 0.25 hours and several days at their evacuation point (see Section 3.3.2.4). The average time spent at an evacuation point was 5.93 hours. Outlined in Section 3.3.2.4, the most common factors influencing peoples decisions to return home following their evacuation included feeling safe and not observing evidence of danger (41%, n=61) and receiving an all clear (39%, n=62). Four survey respondents noted that information on the radio and television informed their decision to return home, while 12 returned home following the deactivation of the tsunami sirens. Five survey respondents also reported that commitments to work and school influenced their decision to return home. While it is promising that 36% of respondents waited for an official all-clear to return home during this event, 41% reported that their return home was influenced by their own judgement or not observing unusual activities of the waves or observation of a tsunami on tidal gauges. This is important when considering that Canterbury's biggest tsunami threat is a distant source tsunami (Jack & Schoenfeld, 2017). Although there will be time for a managed evacuation to occur this hazard, it may take time for the tsunami to arrive. As people may not observe any damage while evacuating, they may attempt to return back into their coastal communities. This indicates that education is required to inform people on when to evacuate, alongside when to return home.

3.4.4 Transportation Method

MCDEM (2016) recommends that when possible, people should walk or bike to evacuate, as this lessens the congestion and leaves the roads open for those who cannot walk or bike, such as elderly, to use a motor vehicle. Despite this, 96% (n=156) of the total respondents reported that they evacuated by car during this evacuation. Only 3% evacuated by walking (n=4) or biking (n=1). The use of cars to evacuate has been observed in other studies (Blake et al., 2018; Fraser et al., 2012; Makinoshima, et al., 2007), however, the rate at which cars have been used is much lower, ranging from 50.2% (Makinoshima, et al, 2007) to 64% (Blake et al., 2018).

The reliance on cars observed in Banks Peninsula and Christchurch can be linked to multiple factors. Firstly, the majority of the evacuees reported evacuating to the homes of friends and family. This was likely because of the time of the evacuation (approximately 2:00 a.m.), and that people wanted to go somewhere to sleep before work and school the next day. Because of this, people travelled beyond the evacuation zones (Figure 3.24), while evacuation routes were scattered across the wider Christchurch area (Figure 3.23), producing an overall average evacuation distance of 11.7 kilometers. Coinciding with this, Fraser et al. (2012) and Makinoshima et al. (2007) have both reported that when people evacuate horizontally along long distances, it is easier to do so using a car. Secondly, 43% (n=66) of the survey respondents who evacuated using a car identified as living with children, while a further 32% (n=52) were living as a family without children (Figure 3.21). Supporting this, 52% (n=79) of those who evacuated in a car reported gathering household and family members as a pre-evacuation action (Figure 3.22). Respondents who evacuated in a car also reported gathering life essentials (31%, n=48), and other items such as blankets, bags, and baby gear (Figure 3.22), which has been identified as an influencing factor in the decision to evacuate by car (Makinoshima et al., 2020). As people wanted to travel to safe locations horizontally across Christchurch, whilst travelling as a family with life essentials, it was therefore easier to do this whilst travelling in a car, contributing to the high use of cars during this evacuation.

3.4.4.1 Congestion

Because of the high reliance on the use of cars, congestion was an issue that many evacuees reported encountering during this evacuation. Many roads, particularly in the denser Christchurch suburbs of Sumner, North Brighton, New Brighton, South Brighton and Southshore, experienced congestion. This was most frequently noted following the activation of the tsunami sirens, which saw a large quantity of the population in these communities evacuate. The congestion was also reported in local media articles, noting grid-lock in South Brighton and blocked up roads in New Brighton (Stuff, 2016; Van Beynen et al., 2016). When reflecting on their evacuation process, ten respondents from Christchurch commented that they felt that there needs to be better planning in place to enable the roading system to cope better with the increase of traffic during future evacuations. Comments included that the roads should have been "*immediately controlled by police with both sides being used to get everyone as far away as possible*" and "*we need a better plan, open both sides of the road to reduce traffic*". This implies that despite a negative evacuation experience due to congestion, in future evacuations many would still evacuate in their cars. Seven respondents reported that they drove on the opposite side of the road to evacuate or observed others doing this. In Japan, where mass congestion was observed during the 2011 Tōhoku tsunami evacuation, Fraser et al. (2012) outlined solutions such as widening roads and developing roading systems to cope better with traffic during an evacuation that were considered to mitigate congestion in future evacuations. There was concern from the authors, however, that incorporating these approaches may exacerbate traffic by encouraging more people to drive (Fraser et al., 2012). As this concern is likely to be an issue in Christchurch and Banks Peninsula, it would be beneficial to continue evacuation education, and incorporate evacuation drills into this education. Evacuation drills help the public improve their confidence in evacuation plans, whilst learning skills to reduce injuries and fatalities in future evacuations (Nakaya et al., 2018). Evacuation drills will help to improve the likelihood that during an evacuation people have been educated on the importance of walking or biking and have practiced this, while also having knowledge on where to evacuate to (Takabatake et al., 2017). This could be achieved through community led evacuation drills that coincide with the tsunami siren testing, or could be through further advertising and promotion of the national *'ShakeOut'* exercise which is organized by NEMA and incorporates an earthquake drill with a tsunami hikoi (walk), promoting both warnings and evacuating by foot (Get Ready, n.d.).

3.4.5 Preparedness

Tsunami preparedness is crucial in improving resilience towards a potential tsunami event. Preparedness ensures that people have the items that they need to survive and have the plans in place to evacuate efficiently (Paton et al., 2008). Previous disaster experience is a strong predictor for higher preparedness towards a hazard such as a tsunami (Dzialek, 2013). It has also been recognised that following an emergency there is an increased sense of urgency from the public to prepare and improve knowledge and understanding of the hazard (MCDEM, 2018b, MCDEM, 2019b). This is because once people have directly experienced a disaster, their risk perception increases, which prompts them to undertake additional actions to be more prepared and reduce the impacts from future events (Walch, 2018). As summarised by Walch (2018) and Hoffman and Muttarak (2017), having experienced a disaster makes it easier for people to imagine future impacts and subsequently prepare. Examples of preparedness being influenced by experience in other hazards (floods, hurricanes, wildfires and earthquakes) have been outlined by Hoffman and Muttarak (2017).

The results of this survey showed a reported improvement in preparedness towards tsunami events following the 2016 Kaikōura earthquake tsunami. Increases in the number of respondents who had participated in the various preparedness actions increased for all actions after the 2016 evacuation. For example, prior to the evacuation only 12% (n=23) of the total respondents had arranged to check on their neighbours. This included 4% (n=1) of Banks Peninsula respondents and 14% (n=22) of Christchurch respondents. Following this evacuation, participation in this action increased to 26% (n=49) of all respondents, 16% (n=4) of Banks Peninsula respondents, and 27% (n=45) of Christchurch respondents.

The increase in preparedness actions that was evident in this survey data is consistent with a trend that has been observed within New Zealand following major disasters. Preparedness actions undertaken by members of the New Zealand public has been shown to increase after major disasters such as the 2010 and 2011 Canterbury earthquakes and the 2016 Kaikōura earthquake (Figure 3.32). For example, prior to the Canterbury earthquakes disaster preparedness was only at 45%, however this increased to 60% in the year following the earthquake sequence (MCDEM, 2019b).

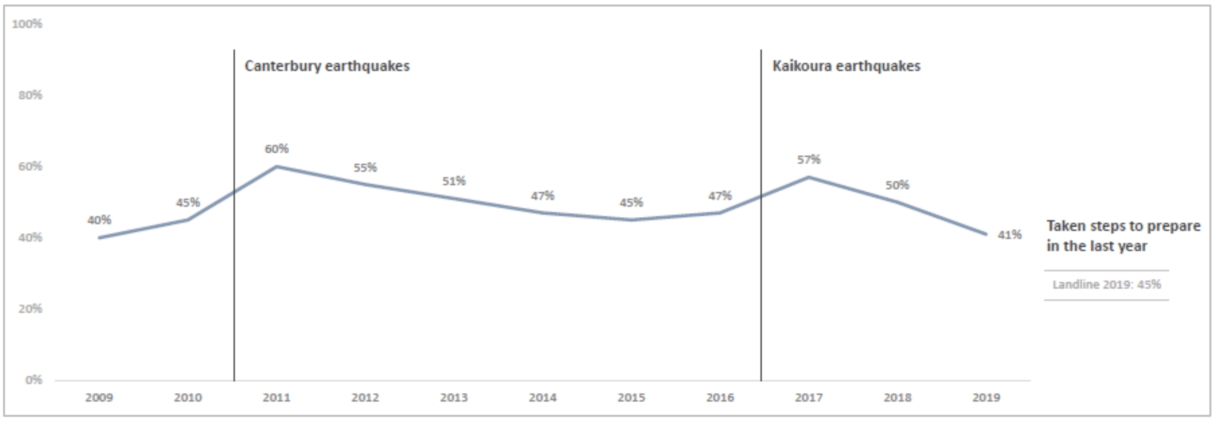

Figure 3.32: Change in disaster preparedness for New Zealand from 2009 to 2019 (MCDEM, 2019b).

When examining the individual responses regarding tsunami knowledge and the need to evacuate before and after the 2016 event, it appeared that most respondents did not in fact feel that their knowledge of tsunami risk had increased. This is different to the overall trend that is shown when looking at the data as a whole (Figure 3.29). This data instead showed that the level of tsunami knowledge had increased for only 38% (n=72) of respondents, while 57% (n=107) of respondents felt that their knowledge of tsunami risk had not changed following the 2016 event (Table 3.13). It is promising however, that of those who felt their knowledge had not changed, 81% (n=47) felt that their knowledge was good or very good. Seven of the nine respondents who felt that their knowledge had decreased identified as females. This seemingly higher percentage of females could be reflective of demographic bias in which the majority of survey respondents were females. Four of the nine respondents who felt their knowledge had decreased were from Sumner. Rather than reflecting demographic bias, this may reflect the survey distribution methodology, where the highest number of surveys were distributed and returned from the Sumner community (see Section 3.2.2 and the start of Section 3.3). This highlights the importance of looking in depth at large data sets in order to obtain a better understanding of how risk awareness and preparedness can change.

Table 3.13: Breakdown of change in tsunami knowledge following the 2016 Kaikōura earthquake tsunami.

Change in level of tsunami knowledge and need to evacuate	Number of respondents	%
No change	107	57%
Increase	72	38%
Decrease	9	5%
Total	188	100%

Although many respondents felt prepared for a tsunami, some respondents found challenges in their efforts to prepare and improve. This was primarily reported by those from Banks Peninsula. One respondent from Akaroa sough clarification on whether the school is in a safe area and was outside of the tsunami evacuation zones. This information would be beneficial for members of this community when planning their evacuation route. A respondent from Birdlings Flat also reported that while they made an effort to learn more information about their tsunami risk, they struggled to find any information relating to this. They noted that although there was general tsunami information, there was a lack of specific information to Birdlings Flat. Similar observations were made when looking on local authorities' websites, where although there was general tsunami risk information, evacuation zones for Christchurch and Banks Peninsula, and evacuation routes for urban areas of Christchurch, there was no detailed tsunami risk information for individual communities, along with no evacuation routes for Banks Peninsula. A respondent from Christchurch reported that they were told the evacuation route they took during this event was wrong commenting that they were told "*don't go by Pages Road, go by Keyes Road*" with no other information provided regarding this. Following the 2016 evacuation, this respondent commented that they had undertaken other aspects of tsunami preparedness, however, did not comment that they had identified an evacuation route. While tsunami evacuation routes have been developed by CCC and are available online for coastal residents to access, the routes are not shown visually, and instead are a list of the main roads that people could take to leave the hazard zone.

3.4.6 Limitations

3.4.6.1 Survey Methodology

This survey took place approximately two years after the Kaikōura earthquake. Some of the survey questions were very specific (for example, what time people evacuated, what they did before evacuating and when they returned home). As a result of the time gap between the event and this survey, some respondents either stated that they could not remember the answers, left the answers blank, or gave an estimation that they were unsure of. As a result, some questions have not been answered as accurately as other questions.

The survey methodology chosen to conduct this research brought some limitations. As previously mentioned, the primary method for distributing the survey was a letterbox drop. A positive of this approach was that this allowed survey respondents to complete the surveys in their own homes at a time that suited them. However, because we were not with the respondents as they completed the surveys, there was no way to control how the questions were answered. Consequently, single choice questions were answered as multi-choice, text style questions were written around questions, and incomplete survey booklets were returned. An issue that was observed in multiple survey books that were returned was that often respondents would reach the map section of the survey, but would not complete the remainder of the questions. As a result of this some of the questions relating to risk perception and changes of awareness of tsunami hazards have had fewer answers than that of other questions.

3.4.6.2 Evacuation Routes

Survey respondents were asked to describe in detail their origin and destination points during the 2016 Kaikōura earthquake tsunami evacuation (Figure 3.23). Respondents were also asked to draw their evacuation route. While many respondents provided full answers for all of these questions, others did not and instead provided general answers. Examples included:

- Naming townships or roads rather than providing a full address;
- Providing origin and destination locations, but not drawing the evacuation route;
- Drawing an evacuation route but not providing origin and destination locations.

When full data was not provided, assumptions were made to digitise the evacuation routes. This mainly involved basing the evacuation route on the quickest suggested route provided by Google Maps. This method was also used to complete evacuation routes for evacuees primarily from New Brighton, South Brighton, North Brighton, Southshore, and Birdlings Flat who often travelled outside of the given map when documenting their evacuation route. Of the evacuation origin, destination, and path information provided, only 17% (n=26) were digitised without the need for any assumptions. All other evacuation routes that were digitised (83%, n=123) required some form of assumption relating to the evacuation route or the location of the origin or destination point. The implication of these assumptions mean that while 149 evacuation routes were produced from this survey, they may not be completely accurate in reflecting the evacuation routes and movements of these populations during the 2016 evacuation.

3.4.6.3 Survey Return Rate

While the results of this study make a positive contribution in understanding evacuation behaviour and reactions to warnings during tsunami events, there were fewer surveys returned than what was anticipated and hoped for. Overall, the return rate of surveys was 12.4% (Table 3.3). However, as shown in Table 3.4, the total return rate of surveys in Banks Peninsula was 7.5%, which was lower than the aimed return rate of 10-15%. The permanent population in Banks Peninsula is relatively low, with the area consisting of many holiday homes. For example, in Akaroa it has been estimated in that there are at least twice as many holiday houses are there are residential houses (Sleeman, 2008). While surveys were distributed to all homes within the evacuation zone within Banks Peninsula, it is likely that surveys were distributed to holiday homes and were not completed and returned, contributing to the low return rate. Despite the return rate in Christchurch being 13.7% (Table 3.4), some areas had lower returns than expected. This occurred in Southshore and South Brighton. At the time the surveys were being distributed the relationship between the local government (CCC) and some of the communities in Christchurch was not positive, with conflict stemming from issues of coastal inundation and re-insurance of coastal properties. People were more concerned with these issues and likely did not see the tsunami evacuation study as a concern, or may have seen that CCC was involved in this research and therefore did not want to assist in this study, contributing to low survey return rates.

3.4.6.4 Demographic Bias

As mentioned at the start of Section 3.3, the majority of survey respondents were females, while the average age of survey respondent was 57 years old. This presents some demographic bias towards older females that must be considered when viewing the results of this study.

3.4.7 Recommendations

This section presents the recommendations that can be made to improve issues that were highlighted in the above section of the discussion. These recommendations contribute to improving evacuation behaviour and interpretation of tsunami warnings in Christchurch and Banks Peninsula.

3.4.7.1 Warning Sources

As explained in Section 3.4.1, was a reliance from communities in Christchurch and Banks Peninsula in receiving official messages (including tsunami sirens, and messages over the radio and social media) to warn and provide information on the tsunami threat during this event. A recommendation to lessen the reliance on official warnings is to continue education on the types of tsunami and the warnings that people can expect. This could occur through the *'Long and Strong, Get Gone'* campaign, which has focused on natural warnings and self-evacuation to decrease the reliance and need from the public for official warnings to prompt evacuation decisions (MCDEM, 2017c). As this is a national campaign, this would improve understanding at a national level, and would be useful for improving evacuation behaviour and interpretation of tsunami warnings for other areas of New Zealand. Similar campaigns could be adopted overseas where a reliance on official warnings has also been observed. Further to this, the use of the tsunami sirens were highly influential in prompting people's evacuation decisions during this event. It would be worthwhile educating the public on when official warnings will be used, with a particular focus on tsunami sirens. This could be achieved through nationwide social media campaigns or advertisements, or through community engagement focusing on areas where this issue was most noted. Further tsunami siren education could be incorporated into the twice-yearly tsunami siren testing, including radio advertisements or newspaper articles. As a reliance on official tsunami warnings has been observed in other evacuation studies (including Blake et al., 2018; Fraser et al., 2012; Hall et al., 2017, similar approaches could be undertaken around other areas of New Zealand or the globe to improve the reliance on this warning source.

During this evacuation, previous risk and earthquake experience influenced how people in Banks Peninsula and Christchurch interpreted the earthquake shaking (explained in Sections 3.4.1 and 3.4.3.1). Consequently, people did not perceive the earthquake shaking to be long or strong enough to generate a tsunami. Therefore, people had low tsunami risk perception during this event and did not self-evacuate. The *'Long and Strong, Get Gone'* campaign has been useful in educating people that earthquake shaking that is of long duration or is strong should prompt evacuation from coastal areas (MCDEM, 2017c; MCDEM, 2018b). This further demonstrates the importance of continuing this education campaign to improve understanding and reactions to tsunami warnings. The results of this research show that previous experience influenced reactions to warnings and highlights that when determining the focus of education campaigns, it is important to consider the risk experience of a community and tailor educational messages to meet the needs of that community. This ensures that people have the education and information to correctly interpret the warning, and can subsequently make appropriate decisions to reduce their risk. For example, educating people who have recently experienced an earthquake event on how to determine if an earthquake may generate a tsunami to inform positive risk reduction and evacuation behaviour.

The response to this evacuation resulted in confusion from the public in knowing when to return home and saw people evacuate multiple times, as explained in Section 3.4.1.1. While the *'Long and Strong, Get Gone'* campaign may have addressed some of the issues surrounding natural warnings and self-evacuation, these examples explained in Section 3.4.1.1 highlight the importance of public education on understanding warnings and knowing when to evacuate, along with knowledge of when to return home. The example relating to the tsunami sirens emphasises the need for there to be clear and consistent guidelines on the use of tsunami sirens, and that this information is shared with the public. This ensures that the public know what to expect from the various warnings during an evacuation and are able to make decisions to decrease their tsunami risk during future evacuations.

3.4.7.2 Pre-Evacuation Actions

During this tsunami evacuation only 8% (n=13) of respondents evacuated immediately (Figure 3.9). All other respondents who evacuated reported that they undertook some form of action, with this being reported in other tsunami evacuation behaviour studies (including Couling 2014; Lindell et al., 2015; Løvholt et al., 2014). While an emphasis on disaster preparedness education at a national level within New Zealand has been the *'Get Ready Get Thru'* campaign, the results of this study indicate that many survey respondents in Banks Peninsula and Christchurch had not done this action. Consequently, people were not prepared to evacuate immediately and had to prepare prior to beginning their evacuation journey (explained in Section 3.4.2). This increased their exposure as they spent more time in the tsunami evacuation zone. This highlights that there needs to be an emphasis on educating the public on tsunami evacuation preparedness to ensure that people have the planning in place to evacuate efficiently in future evacuations. This could be achieved through community engagement. Authorities could hold community meetings to inform communities on their tsunami risk, and complement this with how people can reduce their own risk, including through general preparedness. This ensures that people are aware of why it is important that they prepare and how it can be done, while enabling them to have the capabilities in place to evacuate efficiently in future evacuations. This action could be improved by providing resources to communities, such as check-lists or information on how preparedness can be achieved, to empower people to prepare. This information could be disseminated at public meetings, or local stakeholders and community members could share this information to their fellow communities.

Thirty-nine percent (n=66) of survey respondents reported that they sought further official information before making an evacuation decision (Figure 3.9). While this action has been recognised as a part of the tsunami evacuation process (Makinoshima et al., 2020) and has been observed within other evacuation studies (Lindell et al., 2015), it was made difficult during this event by the confused warning environment, outlined in Section 2.4.1. This saw contradictory information being released by authorities (MCDEM, CCC CDEM, radio and police) which made it difficult for people to make an informed evacuation decision (Kardos, 2017; Lane et al., 2020). This highlights that for future evacuations, authorities need to be collaborating and sharing consistent messages with the public. This is the case for not just tsunami evacuations, but also for other hazards including floods or volcanic eruptions. The public also needs to be made aware of where they can receive accurate information from. Consistent messaging ensures that the public can efficiently receive information and make decisions to reduce their risk. Collaboration and consistency between authorities involved in an evacuation will not only encourage positive evacuation behaviour, but it will also improve the trust the community has in those managing the evacuation (Potter et al., 2018).

3.4.7.3 Evacuation Dynamics

As outlined in Section 3.4.3.3, while evacuation zone information was available during the 2016 tsunami evacuation, this knowledge was not widespread throughout the community, and people struggled to find this information during the 2016 evacuation (Kardos, 2017; Lane et al., 2020). This issue highlights the importance of tsunami risk information such as this being easily accessible for members of the public, and provides an example that other communities (both in and outside of New Zealand) can learn from. The tsunami evacuation zone maps have since been published on more accessible locations on both CCC CDEM and Canterbury CDEM's website (Canterbury Maps, n.d.; CCC n.d.), with 23% (n=44) of respondents noting that they had made themselves aware of this information (see Section 3.3.3). This does, however, require for people to go to these websites to find this information themselves. To increase the reach of this evacuation zones, these maps could be printed and disseminated as brochures – which have been recognised as an effective form of communicating tsunami risk (Mileti et al., 2004) – to communities of Christchurch and Banks Peninsula via a letterbox drop. This would allow for community-specific evacuation zone maps to be created, while also allowing for the brochures to include other tsunami risk information, including sources and warnings. A similar approach could be used for the tsunami evacuation routes which are available online. The evacuation routes (shown visually in Figure 2.25) only provide the names of roads that would guide people out of the hazard zone, however, could be further utilized by being presented on maps to allow people to easily identify themselves and plan their own evacuation route. Community engagement could also be used to present and explain the evacuation zones and suggested routes to communities. This approach was used successfully in Sumner in 2019 to engage with the community and explain changes to the evacuation zones following new modelling. Similar meetings could be held in other communities of Christchurch and Banks Peninsula.

3.4.7.4 Transportation

A reliance on cars was evident in the results of this data. As explained in Section 3.4.4, this was likely linked to people evacuating as families with vulnerable populations (children and elderly), as well as evacuating with pets, emergency gear and travelling long distances to evacuate. To address this, CCC CDEM could work with communities to improve neighbourhood relationships and encourage carpooling. While this still encourages the use of cars to evacuate, it would decrease the overall number of cars on the road, helping to reduce congestion and demand on the roading network in future evacuations. Similar schemes have been implemented in communities of Japan where drivers and vehicles have been designated to assist in transporting vulnerable people during an evacuation to help limit the number of vehicles on the road (Fraser et al., 2012). CCC CDEM could also engage with communities to provide resources such as evacuation zone maps to help households plan their evacuation routes, or hold community meetings to encourage people to identify efficient and safe evacuation routes. In 2019, tsunami evacuation workshops were held in Sumner and were facilitated by CCC CDEM, GNS Science and the University of Canterbury Tsunami Research Group. While the primary focus of the workshops was to critique a tsunami evacuation model (described in Section 2.3.2.3.1), the workshops were successful in that many community members attended, and people were prompted to discuss their evacuation routes. The workshops also gave researchers and CCC CDEM staff the opportunity to engage with communities about how to evacuate, along with the evacuation zones. It would be beneficial to have similar workshops in other areas of Christchurch and Banks Peninsula to facilitate discussion of evacuation routes, which may increase people's confidence in their ability to evacuate by walking or on foot. People in Christchurch and Banks Peninsula could also be encouraged to participate in the annual *'ShakeOut'* tsunami evacuation exercise. Participating in this event may improve people's confidence in their evacuation plans by having pre-identified evacuation routes and destinations, while practicing the routes ensures people are aware of the time required for them to evacuate.

While the use of cars have been recognised in other tsunami evacuations (outlined by Makinoshima et al., 2020), the reliance on cars during this evacuation is likely a contextual factor linked to the time of day in which this evacuation took place. Even if extensive tsunami risk education and engagement took place to encourage people to walk or bike, there is still a high chance that there would be a high use of cars in future evacuations. Shown in Figure 3.30, media coverage of previous tsunami events was recognised as a valuable information source in informing evacuation decisions. The issues surrounding the use of cars during evacuations, and the congestion and increased exposure this can result in, have been documented during other evacuations (including Blake et al., 2018; Fraser et al., 2012; Makinoshima, et al., 2007). It would be beneficial when engaging with communities to incorporate and highlight issues that have been documented relating to evacuating by cars from previous tsunami evacuations. This may help people understand why it is an issue and help improve this evacuation behaviour.

3.4.7.5 Preparedness

Research has shown that despite an urge to improve preparedness following a disaster, over time people can become complacent and preparedness efforts decrease (Bird & Dominey-Howes, 2008; Couling, 2014; Kammerbauer & Minnery, 2019). This trend has been evident within New Zealand at a national level following both the 2010-2011 Canterbury earthquakes and the 2016 Kaikōura earthquake (MCDEM, 2019b). A contributing factor is as time passes, people forget the consequences of previous events (Siripong, 2011) and so do not perceive the risk of future events to be as high or as damaging. While it is promising that preparedness actions and knowledge of tsunami hazards and the need to evacuate have increased in respondents from Banks Peninsula and Christchurch following this event, there is a chance that these areas will follow a similar trend to the rest of New Zealand where efforts and knowledge decrease over time. This highlights the importance of continued tsunami risk education to ensure that people are aware of the risk tsunami pose and are prompted to prepare. This could to be coupled with preparedness campaigns that the public can follow and adopt. Using both of these in the same approach ensures that people know what their tsunami risk is and are aware of what they can do to reduce their risk. For example, in a regional source tsunami there may not be time to release official warnings (Jack & Schoenfeld, 2017). People therefore need to be educated on how to interpret natural warnings for these tsunami sources, and have the capabilities to allow for immediate evacuation to reduce their risk. This includes having pre-established evacuation routes and go-bags that are in easily accessible locations.

3.4.8 Future Work & Research

3.4.8.1 Evacuation Modelling

This research aimed to determine the tsunami evacuation dynamics made by those in Christchurch and Banks Peninsula during the 2016 Kaikōura earthquake tsunami evacuation. Of particular interest was how people evacuated, where they evacuated to and from, when they evacuated, where congestion was, and the travel speed of the congestion. This data can be used to inform evacuation modelling. Completing evacuation modelling for these communities would allow emergency managers to better plan for evacuations by having an increased understanding of how people evacuate, alongside identifying issues such as congestion and bottlenecks (Liu & Lim, 2018; Wafda, 2013). This would guide future evacuation planning in Canterbury and wider New Zealand. Evacuation modelling will be addressed in Section 4 of this Masters research.

3.4.8.2 Intended Evacuation Behaviour Study

Survey intention data has been found to have a degree of validity when predicting actual behaviour during evacuations (Whitehead, 2005). Evacuation intention studies have been carried out for tsunami (Arce et al., 2017; Currie et al., 2013; Fraser, et al., 2013; Hall et al., 2017). It would be useful to continue researching evacuation behaviour in Christchurch and Banks Peninsula by conducting a study on intended tsunami evacuation behaviour for a future evacuation. Following the 2016 event, MCDEM promoted the message of *'Long or Strong, Get Gone'* to promote self-evacuation and tsunami warnings. A study on intended evacuation behaviour would be beneficial for authorities to gain an understanding of the success of this campaign, as well as provide insight on the risk perception of the public towards tsunami and their level of understanding towards tsunami warnings. A study such as this may suggest other areas of tsunami evacuation behaviour that need to be targeted. Additionally, as the 12% survey return rate for this study was lower than anticipated (Section 3.4.6.3), a study on intended behaviour will further improve understanding of evacuation behaviour and knowledge in these locations.

3.4.8.3 Evacuation Planning

3.4.8.3.1 Population Changes

For future evacuation planning, it is important to incorporate the spatio-temporal changes in the population. Urban populations are not static (Kobayashi et al., 2011), with people coming and going into areas for work, recreation, education or leisure (Tomsen et al., 2014). Diurnal and seasonal variation in the population may influence evacuation behaviour and congestion in future tsunami evacuations. This evacuation, in the middle of the night, saw people travel all over Christchurch, contributing to a reliance on using cars. This may not be the case during an evacuation during the day, as people may choose to evacuate to evacuation centres that may be closer, subsequently not needing to evacuate in a car. Contrasting this, people who leave their communities for work may attempt to return home to collect and evacuate with other family members, pets or valuables, as was observed in Japan during the 2011 Tōhoku tsunami (Fraser et al., 2012). Furthermore, an evacuation during the peak summer season may mean a higher number of people in areas of Bank Peninsula, as well as in Sumner or New Brighton who may all evacuate in cars. Variations in the origin of evacuation routes could influence the evacuation route and the distribution of congestion. Anticipating and planning for a range of evacuation scenarios by considering the spatio-temporal changes, and relating this to the evacuation transportation mode that may be used, will allow for more accurate and realistic evacuation modelling. This will enable emergency managers to have a better understanding of where congestion may occur, and focus traffic management to these areas. This information can also be used to improve evacuation plans, as by anticipating the number of people who may visit evacuation centres, the supplies required at these centres can also be anticipated, allowing centres to be more prepared for evacuees.

3.4.8.3.2 Vertical Evacuation

Many of the areas where congestion and a high usage of cars were observed have little redundancy in the roading network to handle additional traffic during a mass evacuation. Particularly concerning are New Brighton, South Brighton, and Southshore where the communities themselves are situated between the ocean and the Avon-Heathcote Estuary, and consequently there are few exit points to use to evacuate inland. With an increase in road traffic during this evacuation, congestion rapidly built up, making it harder for people to evacuate. This increased the tsunami risk of people in these communities. This issue is likely to occur in future evacuations and will likely result in people remaining in these areas, thereby increasing their tsunami risk. Subsequently, a lack of mobility may see people remain during a tsunami evacuation. Vertical evacuation is a solution that could be considered for these communities. This would enable people who cannot evacuate fast enough – either due to congestion or mobility – to seek shelter. During the 2011 Tōhoku tsunami, more than 5,428 lives were saved by evacuating to 37 vertical evacuation structures (Fraser et al., 2012). In New Zealand, MCDEM (2018c) have released a guideline on assessing and planning for vertical evacuation structures, which will be complemented by a guideline outlining design criteria and engineering specifications. Following the release of this second guideline, it would be beneficial to research the role vertical evacuation structures may have within communities of Christchurch.

3.5 SUMMARY & LINK TO NEXT CHAPTER

This chapter addressed Objective 2 of the thesis: Analysis of behaviour and actions to the 2016 Kaikōura earthquake and tsunami. A survey questionnaire was used to gather primary data, including evacuation triggers, pre-evacuation actions, evacuation methods, and changes in risk perception and preparedness. These results were analysed and compared to other local and global studies to characterise broad evacuation behavioural trends and identify factors that were influential in the evacuation decision making process.

Survey data can be used to inform evacuation modelling, improving the accuracy and realism of the evacuation scenarios being modelled. The survey results presented in this chapter, along with tsunami risk management strategies that have been implemented already by CCC CDEM, Canterbury CDEM and NEMA, and exposure and vulnerability data, will be used to inform an evacuation model for Banks Peninsula. This model is presented in the following section (Section 4).

4 BANKS PENINSULA EVACUATION MODELLING

4.1 INTRODUCTION

This chapter addresses Objective 3 of the thesis: Evacuation modelling. The chapter is structured by first presenting a description of the ArcCASPER evacuation tool used for this analysis. This is followed by the method and inputs required to apply this tool to Banks Peninsula to produce a vehicular evacuation model. The purpose of the evacuation modelling is to assess the ability of coastal communities in Banks Peninsula to reduce their tsunami risk by evacuating. The results of the modelling are then presented. Following this is a discussion of the results, which includes a reflection on the suitability of the CASPER tool for evacuation modelling in Banks Peninsula. Recommendations to ensure efficient evacuations in the future are presented within this discussion. Finally, future research relating to the method and application of this evacuation model is presented.

4.2 ARCCASPER

As identified in Section 2.2.2, Banks Peninsula is exposed to tsunami that may originate from local, regional, or distant sources. These small rural communities are unique regarding their vulnerability to this hazard. Although these communities are isolated with relatively low normal resident populations, Banks Peninsula's landscapes, history, heritage, and recreational activities attract national and international visitors (Sleeman, 2008). These include a large number of day visitors, as well as those who stay at private holiday homes or commercial accommodation (Sleeman, 2008); thus, there can be significant daily and seasonal variation in population exposure. Steep slopes surround many of Banks Peninsula's populated places, and there are few roads leading in and out. During a tsunami event, there would likely be pressure on the road network to accommodate evacuating vehicles. Periods of high visitor numbers will lead to more cars on the roads, which could increase the time required for people to evacuate from exposed areas. For this Masters research, ArcCASPER (Shahabi & Wilson, 2014) will be used to model vehicular evacuations for Banks Peninsula. The choice to use this modelling technique was made based on the data available and the advantages of the tool outlined in Table 2.3.

ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing) is an extension of the *Network Analyst* tool in ArcMap (ESRI, 2011). The tool features an algorithm that produces evacuation routes to the nearest safe area for evacuees, and considers minimising hazard exposure and road network capacity constraints, while seeking to reduce travel times and optimise evacuee flows to minimise congestion (Shahabi, 2012; Alabdouli, 2015; Trindade et al., 2018). The algorithm can also differentiate between the size, density and flow of population when generating evacuation routes (Trindade et al., 2018).

ArcCASPER features three modelling methods:

- *Shortest Path*. This is the most traditional method of evacuation route modelling which calculates the shortest path (Harris et al., 2015). This approach ignores road capacities, which speeds up model processing but also limits output accuracy (Shahabi, 2012).
- *Capacity Constrained Route Planner (CCRP)*. This produces evacuation routes that are constrained by road capacities. For example, on a narrow road segment, priority is given to those with a longer evacuation time. Once the segment is saturated and has bottlenecked, the algorithm redirects the remainder of evacuees (Shahabi, 2012).
- *Capacity-Aware Shortest Path Evacuation Routing (CASPER).* Evacuees are sorted by distance from their origin point to the closest safe area. Starting with the evacuees farthest away, the shortest route is identified and the evacuee assigned to it. This process is repeated until all evacuees have been assigned an evacuation route (Shahabi, 2012). Based on the number of assigned evacuees and capacity of the road edges, the algorithm dynamically updates each route segment travel cost during the analysis to minimise evacuation time (Shahabi, 2012). The overall result is a set of routes that guide each evacuee to the best safe area based on their origin point (Shahabi, 2012).

The CASPER method is considered to be a promising tool in modelling evacuations when the demands on the road network have been determined by behavioural analysis (Alabdouli, 2015). For this study, the CASPER method will be used model tsunami evacuations in Banks Peninsula, and will be informed by empirical data collected from the tsunami evacuation behaviour survey questionnaire (Section 3), along with tsunami risk management strategies that have been implemented already by CCC CDEM, Canterbury CDEM, and NEMA, and exposure and vulnerability data. Incorporating results of the evacuation behaviour survey questionnaire will improve the validity of the survey results.

The CASPER algorithm integrates the capacity of the transportation network with its length to predict travel speed under different traffic models (Alabdouli, 2015; Trindade et al., 2017). This process uses a graph (road network), a traffic model, source points and destination points as inputs. CASPER utilises the capacity of the transportation network and the traffic flow as inputs into the selected traffic model and produces a new speed estimate for each segment of the transportation network based on the road saturation density per unit capacity (Alabdouli, 2015). The tool continues to update the speed estimate and generate evacuation routes for each evacuee whilst minimising evacuation time and congestion until all evacuees have been directed to safe zones (Alabdouli, 2015).

CASPER requires four inputs to model the evacuation routing (Figure 4.1):

- *Graph (road network).* The graph represents the road network and comprises of vertices and directional edges. Each edge has an impedance and capacity value which change throughout the evacuation (Shahabi & Wilson, 2018);

- *Source points*. These represent the evacuee locations/origin points and contain the vertices of where the evacuees are evacuating from. Each source point generates just one path to the destination point, while the evacuation path created is a set of connected road segments that direct the evacuee to safety (Alabdouli, 2015);
- *Destination points*. These represent the safe zones/evacuation locations. Similar to the source points, destination inputs contain the vertices of where the evacuees are evacuating to (Alabdouli, 2015);
- *Traffic model*. The traffic models help CASPER predict traffic delays on the road segments. CASPER has five traffic models available that the user can select from: Flat, Step, Linear, Power, and Exponential. These models represent real-world traffic and ensure that there is an efficient flow of evacuees with minimal congestion (Alabdouli, 2015; Shahabi & Wilson, 2018; Trindade et al., 2017).

The graph, source, and destination points are input by the user, while the traffic model is selected from one of the five available models within the CASPER extension. As explained below in Section 4.3, the **Power** *traffic model* was used for this research.

The CASPER extension produces three primary output tables (Figure 4.1): Routes, edgestats, and flocks. Routes consist of polylines representing evacuee paths to the safe zones they (evacuees) have been routed to (Shahabi, n.d). Each route has attributes such as the evacuation travel time known as the evacuation cost, number of vehicles on each evacuation route, and the name of the safe zone that the path will be arriving at. The edgestat table lists all road segments utilised by CASPER in solving the evacuation (Shahabi, n.d.), and helps users understand where there may be issues in road capacity and bottlenecks. Information within this table includes the number of cars that will pass the road segment at some stage during the evacuation, the travel cost of the road segment (both considering congestion and the original cost), and the congestion ratio (which is a number between 1 and 10,000) (Shahabi, n.d). The flock output acts as an evacuation simulation and produces a single point for each evacuee at each time step (Shahabi, n.d). Each point has attributes such as name of the evacuee the point relates to, travel cost at that point, velocity, distance travelled, and evacuee status (moving, stopped, collided, or end of evacuation travel). Further detail on CASPER outputs are presented by Shahabi (n.d.).

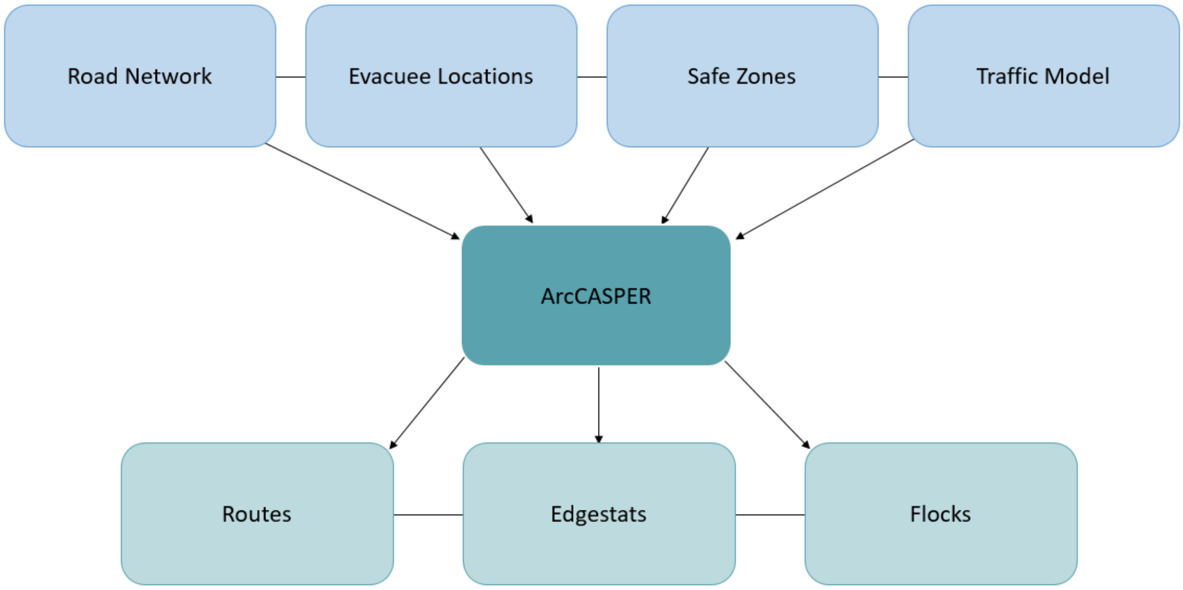

Figure 4.1: Inputs to and outputs from the ArcCASPER evacuation tool.

The following section of this chapter will explain the data used to inform the road network, and the source and destination points (evacuee locations and safe zones). Following this, the results of the evacuation modelling will be presented, along with a discussion of these results and the suitability of CASPER as a modelling tool for Banks Peninsula.

4.3 INPUT DATA AND MODELLING

A vehicular evacuation model was applied for three scenarios at two different speeds for areas of Banks Peninsula (shown in Figure 4.2). Ten areas were chosen based on their tsunami risk, along with local knowledge that these areas can have an increase in summer population (Sleeman, 2008). The three evacuation scenarios were intended to cover maximum exposure:

1. Peak day traffic;
2. Peak night traffic;
3. Normal resident traffic.

Where communities did not have any commercial accommodation points, the normal resident traffic scenario also represented the peak night traffic scenario.

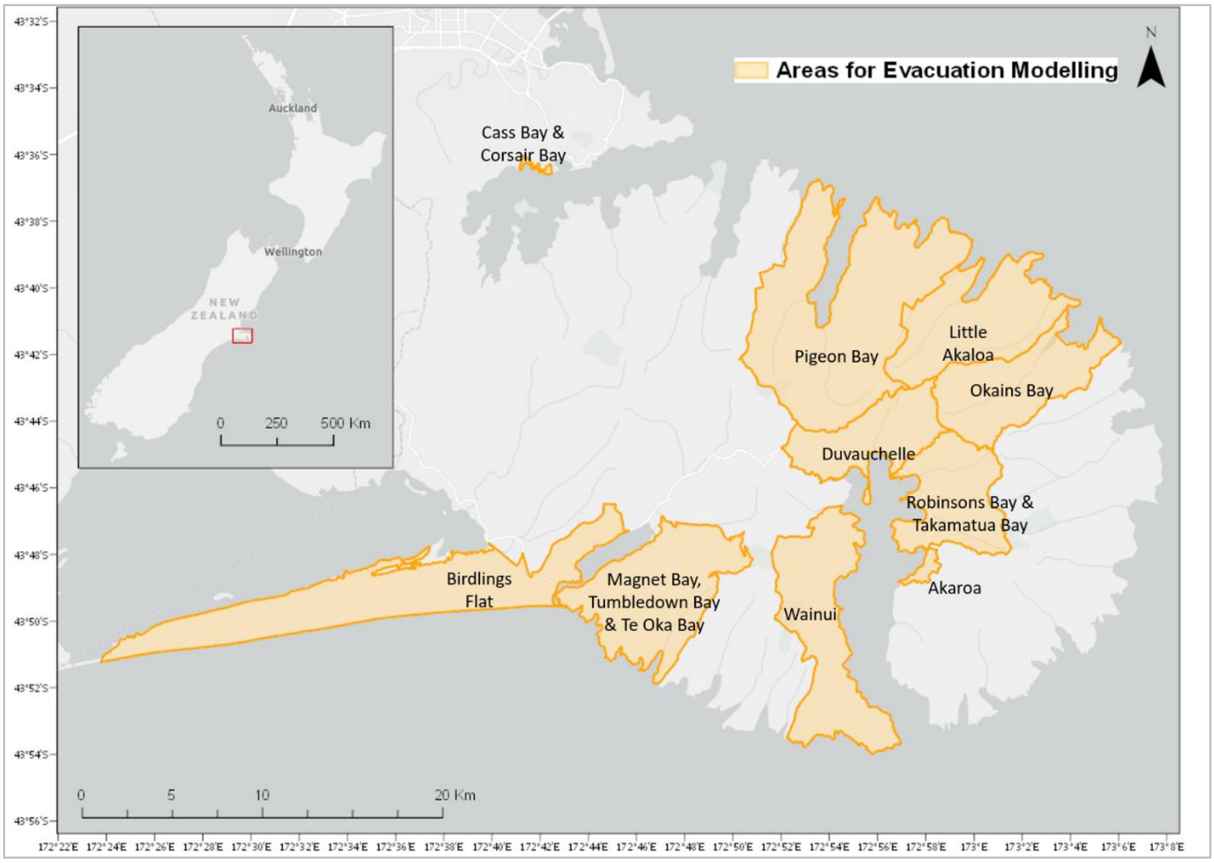

Figure 4.2: Areas of Banks Peninsula where CASPER modelling was performed.

Figure 4.3 shows the settings used for the evacuation modelling. Many of the properties were left as default. As recommended by the creators of the tool, the *Dynamic Mode* was set as **Smart**; this meant that every time the road network changed, the affected vehicles were identified and rerouted. The **Power** *Traffic Model* was used to enhance evacuation time and congestion prediction (Alabdouli, 2015). The CASPER model assumes that all evacuees begin their evacuation journey immediately, and does not account for any pre-evacuation behaviours that may take place between receiving a natural or official tsunami warning, and beginning an evacuation journey. The *Intl Delay Cost Per Evacuee* setting represents the time between evacuees that are sharing their start location (where one origin point represents multiple evacuees). This value was left at the default setting of 0.01.

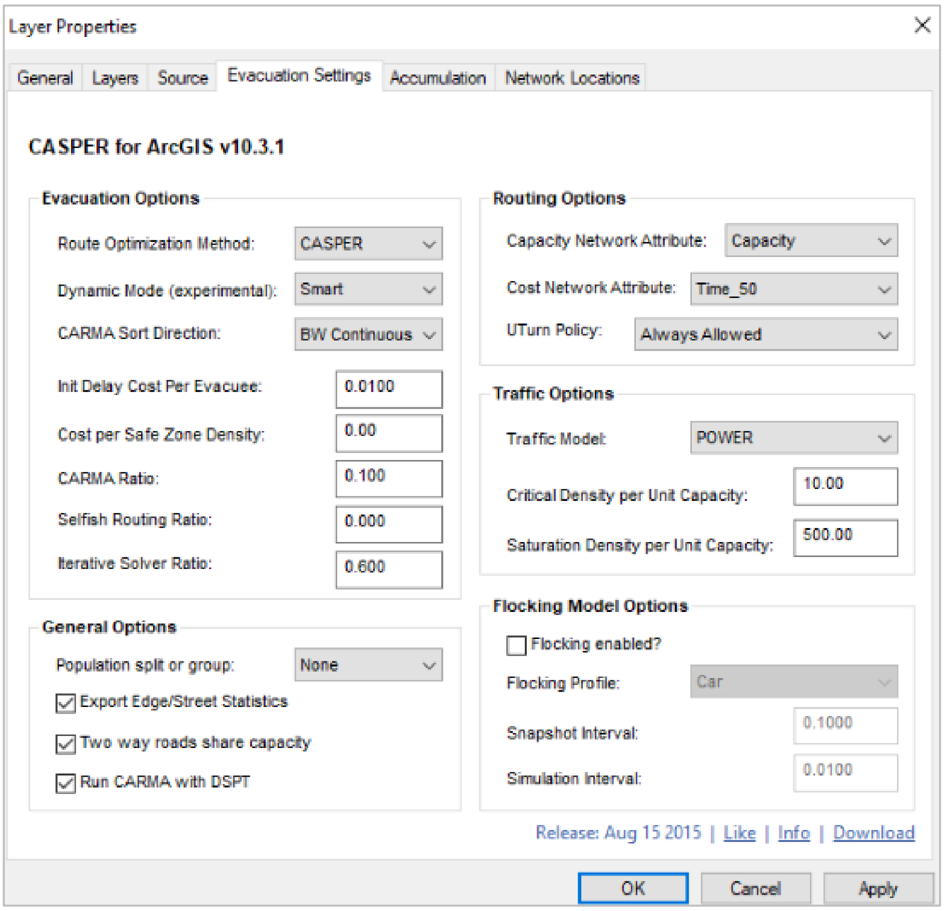

Figure 4.3: CASPER settings used in this research.

4.3.1 Modelling Inputs

Inputs for the evacuation modelling were informed by tsunami risk management strategies that have been implemented already by CCC CDEM, Canterbury CDEM, and NEMA, exposure and vulnerability data, and where appropriate by the evacuation survey results from Section 3. The survey return rate for Banks Peninsula was 7.5% (Table 3.4), with only 28 surveys returned and only 50% (n=13) of these respondents actually evacuating during this event (shown in Figure 3.11 and Figure 3.13). To improve the validity of using the survey data to inform the modelling, the decision was made to use survey data reported by both Banks Peninsula and Christchurch respondents. Results for the following survey questions informed the evacuation modelling:

- How did you travel to your evacuation destination?
- Where did you evacuate to (including the documented evacuation route)?
- Did you encounter any traffic congestion or were you aware of congestion problems?
- On average, how slow do you think traffic was moving in these congested areas?
- How long (did pre-evacuation actions take) before you actually started evacuating?

A vehicular evacuation model was produced for Banks Peninsula. This was based on 100% of Banks Peninsula respondents reporting that they evacuated in a car, while 96% (n=156) of the total survey respondents (Banks Peninsula and Christchurch) also reported this pre-evacuation action (Section 3.3.2.4).

4.3.1.1 Road Network

CASPER requires an up-to-date road network with no inaccuracies (Harris et al., 2015). For this research, the road network data was sourced from Land Information New Zealand (LINZ) (LINZ, 2020b) and was clipped to only include roads in Banks Peninsula. The road network was further clipped to each study area (Figure 4.7 and Figure 4.8), and inspected using base map imagery to ensure that it was complete, spatially accurate and topologically correct. Minor changes made were:

- Adding roads not in the original network;
- Spatially editing polylines to align with base map imagery;
- Ensuring separate polylines in a route were connected topologically;
- Ensuring that polyline intersections were connected topologically.

Once these changes were made, the road network attributes were altered to include what was required to run the model. This included road length, number of lanes (assumed to be two for all roads), speed (both normal New Zealand road speed of 50 km/hr and the average congestion speed from the evacuation survey (28.1 km/hr)), and route travel time (calculated as road length divided by the speed).

The original road network data sourced from LINZ had no information on the number of lanes or road speed. Therefore, assumptions were made. While some areas are known to have narrow roads (including the roads leading into Pigeon Bay, Okains Bay, and the smaller bays on the south of Banks Peninsula), there were few data relating to where the road lanes widened or increased. Therefore, it was assumed that all roads had two lanes. For the normal road speed of 50 km/hr, this is typical for built-up areas of New Zealand. While there is variation in posted road speed among Banks Peninsula areas – both below and above the typical speed of 50 km/hr – it was unknown specifically where these variations occur. Therefore a conservative approach was taken in assigning all roads 50 km/hr.

A second evacuation speed was informed by the survey data reporting the average congestion speed respondents encountered or observed during the 2016 evacuation. Twenty-eight surveys were returned from Banks Peninsula, however, only one respondent reported observing congestion (Section 3.3.2.4). A further five respondents provided an estimation of the congestion speed, which ranged from 50 km/hr to 100 km/hr, with an average speed of 85 km/hr (see Section 3.3.2.4 and Appendix D). To improve the validity of the results to this survey question, the decision was made to include the average congestion speed reported by both Banks Peninsula and Christchurch survey respondents. This allowed for a total of 104 congestion speed estimates to be included, with an average speed of 28.1 km/hr (Section 3.3.2.4). This estimate was used for the evacuation model.

4.3.1.2 Evacuee Locations

The CASPER modelling algorithm assumes full community compliance in the evacuation. Two methods, discussed below, were used to determine the source points of the evacuee locations.

4.3.1.2.1 Building Inventory

A building inventory was created to categorise Banks Peninsula building use within the tsunami evacuation zones. Firstly, polygons of building footprint data were obtained (LINZ, 2020a). Building point data were then obtained from RiskScape. The RiskScape data are based on QV records, and contain attribute information such as year of construction, construction type, number of occupants and building use category. For the purpose of this exposure inventory, only the building use category was of interest. Several errors were found in these two datasets:

- Small structures such as garages and silos had both footprints and points indicating they were residential dwellings;
- Buildings were listed with the wrong use category. For example, buildings that were commercial accommodation were often listed as residential dwellings;
- Larger buildings had multiple points listing multiple building categories;
- Buildings were missing from both the building footprint and RiskScape datasets.

To address these errors, Google Earth and Google Street View were used to determine the building use. The primary focus of this exercise was to determine whether buildings were residential dwellings or if they had other uses, and to identify the buildings that were sheds and remove them from the dataset. Where the building use and type could not be verified from Google Earth or Google Street View, a field survey was conducted. This allowed for building footprints to be drawn around newer buildings, accurate use categories to be assigned, and for smaller structures to be removed from the dataset.

The original RiskScape dataset had a total of 1,587 buildings within the Banks Peninsula tsunami evacuation zones, while the building footprint data showed 2,887 footprints. Following the use of Google Earth, Google Street View, and the field survey, the number of buildings was refined to 1,097. A comparison of the number of buildings for each use category for the RiskScape data and the refined data is shown in Table 4.1. Figure 4.4 and Figure 4.5 provide examples of the building inventories for the communities of Akaroa and Little Akaloa. Building inventories produced for the remaining study areas are can be viewed in Appendix F.

Table 4.1: Comparison of number of buildings for each use category from the original RiskScape Data and the refined data.

Building Use Category	RiskScape Data	Refined Data
Residential	1502	797
Business	53	166
Commercial Accommodation	9	60
Community	6	24
Education	3	7
Resthome	1	6
Religious	2	10
Emergency Services	0	2
Other*	11	25
Total	1587	1,097

*Note that 'Other' category includes 6 buildings where the use is listed as other, and 5 which are listed as categories ignored for this study (farm and lifestyle uses).

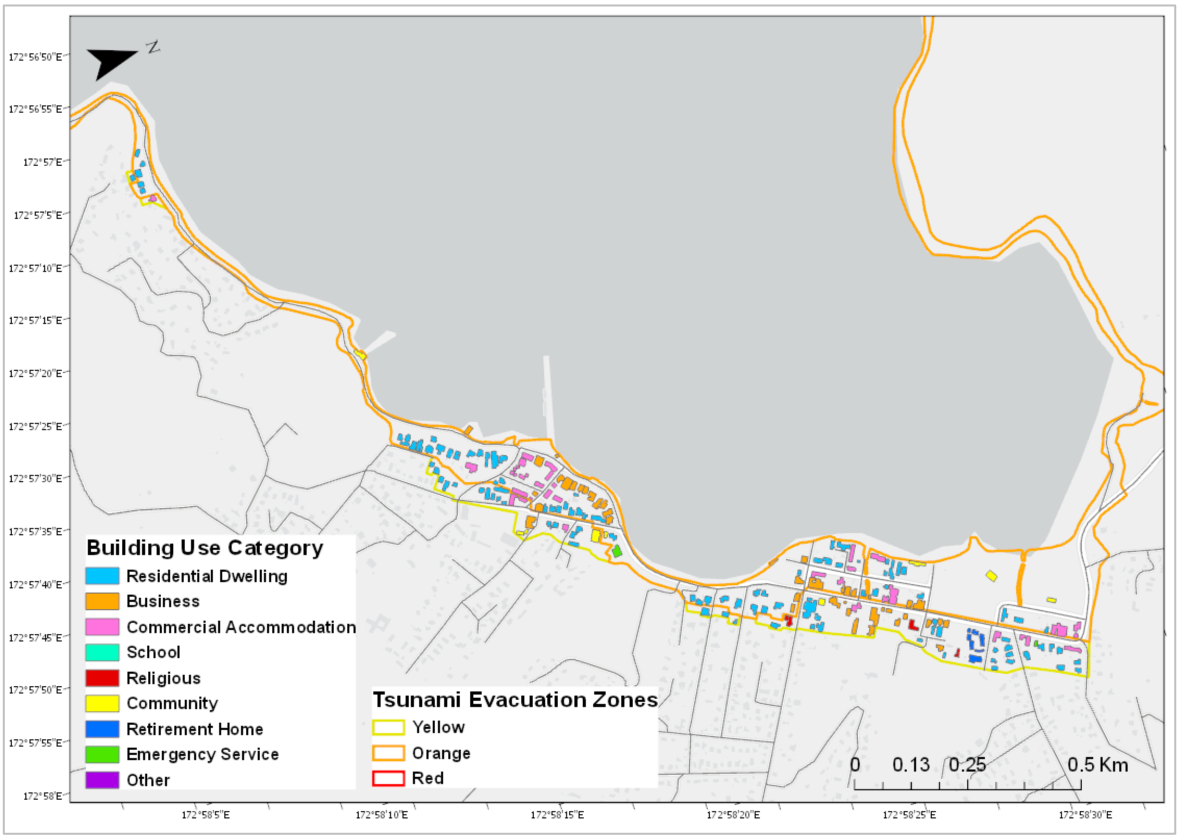

Figure 4.4: Building inventory within the tsunami evacuation zones in Akaroa.

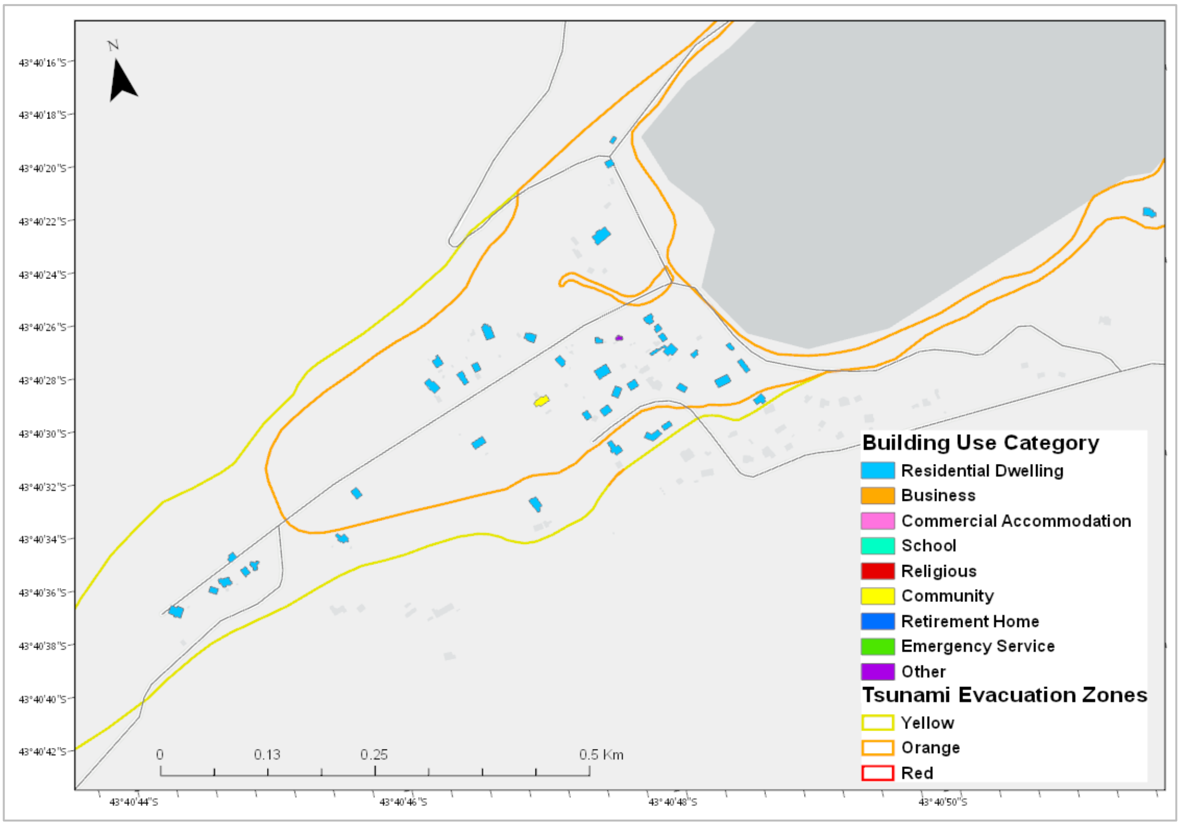

Figure 4.5: Building inventory within the tsunami evacuation zones in Little Akaloa.

The following assumptions were made when creating the building inventory:

- A conservative approach was taken when determining the building use category. For example, in Akaroa there was a building that fit in the category for both commercial accommodation and business. As a worst-case scenario was to be used for this study, the building was assigned the category of commercial accommodation;
- In many areas where locations of commercial accommodation (hotels, motels and camp grounds) were known, there were other buildings surrounding some of these facilities. Here, all buildings were assumed to be accommodation;
- Rather than view commercial and industrial activity separately, they were included in the same category (business);
- Many of the houses in Banks Peninsula are holiday houses. It was estimated in 2003 that there were twice the number of holiday houses compared to residential houses in Akaroa (Sleeman, 2008). There is limited information on the location of holiday houses compared to residential houses, which impacts the occupancy rate and where vehicles would be evacuating from. Therefore, for this research all residential buildings (including permanent residents and holiday houses) have been assumed to be occupied.

For the purpose of this evacuation modelling, centroids of residential and commercial accommodation building polygons were used to represent evacuee points (Figure 4.7 and Figure 4.8). For residential buildings, each centroid represented one vehicle, with the assumption that each family evacuated in one vehicle. Commercial accommodation businesses throughout Banks Peninsula within the tsunami evacuation zones were researched to determine the number of rooms at each business. Travel websites and websites for the specific businesses provided room numbers for 17 out of 22 businesses (see Appendix F for further details). For the five accommodation businesses with an unknown number of rooms, the average of the known number of rooms was used (six rooms). For the purpose of the evacuation modelling, it was assumed all rooms were occupied, and that each room represented one vehicle evacuating.

4.3.1.2.2 Field Observations

To estimate the number of vehicles for a day time peak exposure scenario, visits were made to locations of interest to observe and estimate the number of vehicles present within the tsunami evacuation zone. Only vehicles that were stationary were included in this study. This included vehicles parked on the side of the road or in carparks. Vehicles that were parked on private property were excluded. Table 4.2 provides the total number of vehicles observed in each location and Figure 4.6 shows examples of vehicles observed. The location and number of these vehicles are used to inform origin points of evacuees (refer to Figure 4.7, Figure 4.8 and Appendix G). It was assumed that each vehicle observed inside the evacuation zones would evacuate to a safe zone during a tsunami evacuation, and that evacuees were already in their car ready to evacuate.

Table 4.2: Location, date and number of vehicles observed during field observations in Banks Peninsula communities.

Location	Date of visit	Number of vehicles
Cass Bay	11/01/2020	12
Corsair Bay	11/01/2020	65
Duvauchelle	11/01/2020	100
Okains Bay	11/01/2020	129
Pigeon Bay	11/01/2020	40
Wainui	11/01/2020	30
Akaroa	2/02/2020	460
Little Akaloa	2/02/2020	12
Robinsons Bay	2/02/2020	2
Takamatua Bay	2/02/2020	13
Birdlings Flat	3/02/2020	26
Magnet Bay	3/02/2020	7
Te Oka Bay	3/02/2020	9
Tumbledown Bay	3/02/2020	60

Figure 4.6: Photos taken during the field observations showing the location and numbers of vehicles that were parked on the side of the road. A-D are Akaroa, E is Duvauchelle Camp Ground, F is Tumbledown Bay, G is Wainui and H is Okains Bay

4.3.1.3 Safe Zones

During a tsunami evacuation, recognised protective actions involve evacuating inland, to higher ground, or vertically up a designated tsunami evacuation structure (Power & Leonard, 2013). The border of the tsunami evacuation zones represent areas where local authorities do not believe there to be risk of inundation (Jack & Schoenfeld, 2017). For this study, points representing safe zone locations were placed on the road network on the border of the tsunami evacuation zone (Figure 4.7 and Figure 4.8) (Canterbury Maps, n.d.). The capacity for each safe zone was set to -1, indicating that each safe zone would be able to hold an unlimited number of evacuees.

Figure 4.7 and Figure 4.8 provide examples of inputs (road network, evacuee points, and safe zones) required to run the CASPER model for the communities of Duvauchelle and Okains Bay. Further examples can be viewed in Appendix G. Details on the evacuees that were input into each category (residential, accommodation, and car locations) for all of the communities can also be viewed in Appendix G.

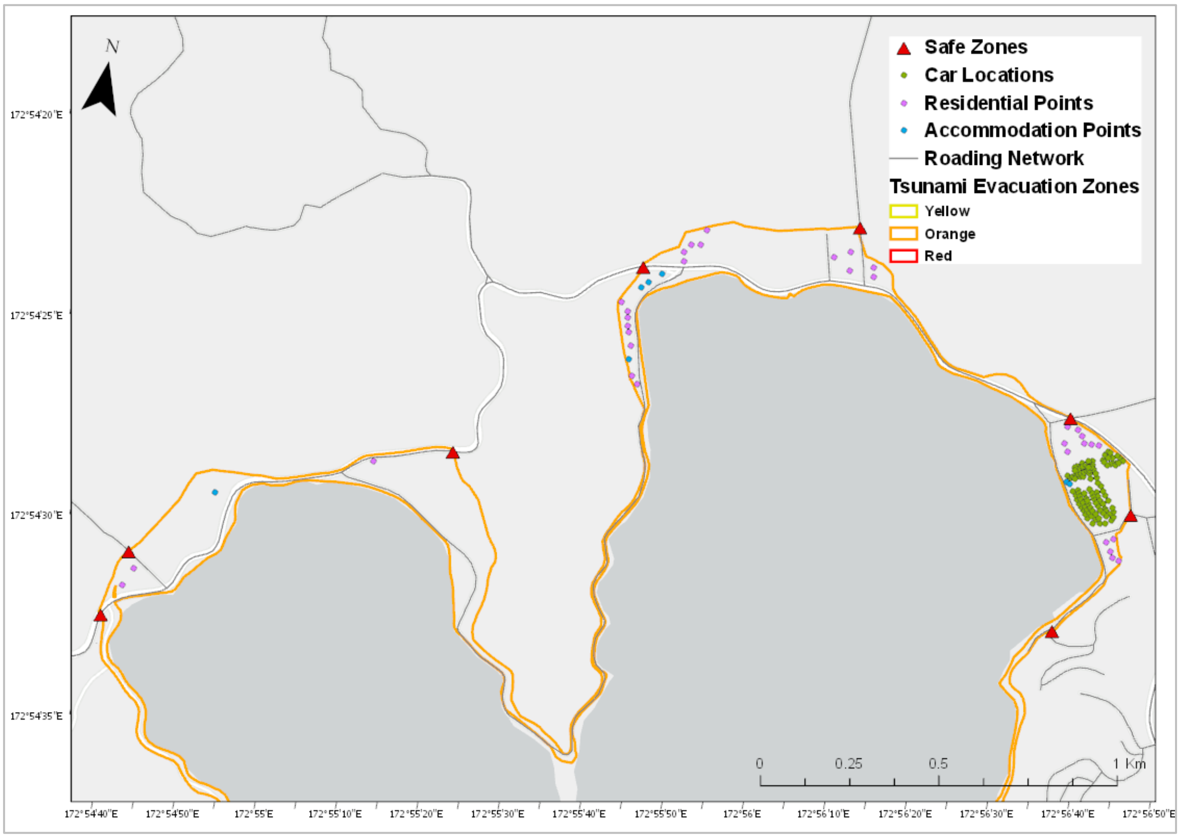

Figure 4.7: Origin points and safe zones that were used to inform the evacuation modelling for Duvauchelle.

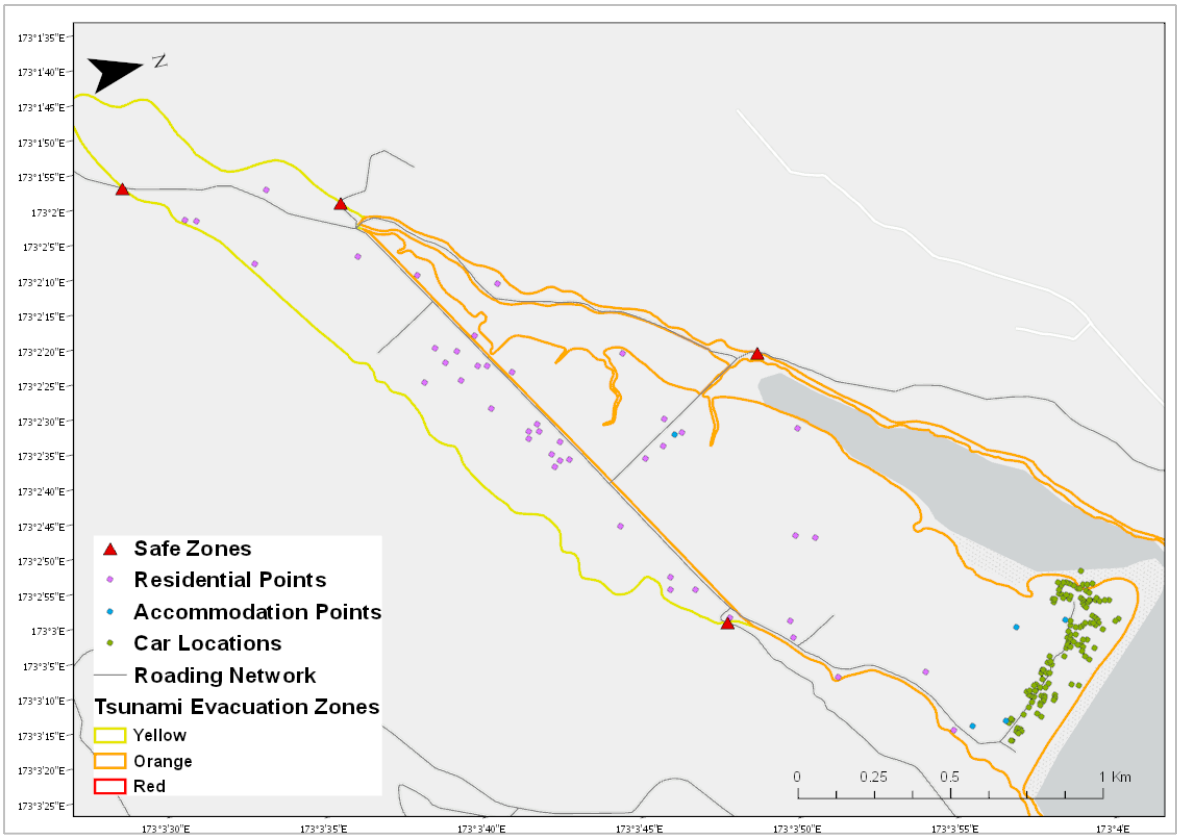

Figure 4.8: Origin points and safe zones that were used to inform the evacuation modelling for Okains Bay.

4.3.1.3.1 Reduction in Safe Zones

Initial evacuation modelling was conducted where all possible safe zones were input into the CASPER modelling algorithm. Additional modelling was undertaken to look at the impact of reducing the number of safe zones and the implication this may have on congestion and the evacuation cost. In this modelling, where appropriate, the safe zones were informed by the evacuation destination data recorded in the evacuation behaviour survey. Decreasing the number of safe zones and incorporating survey data of where people evacuated to during the 2016 evacuation will help to improve the accuracy and realism of the modelling (Kubisch et al., 2019). It will allow for the following scenarios to be replicated:

- If people did not know where to evacuate to and followed other vehicles to the same safe zone;
- If there were pre-existing roadworks on an evacuation route reducing the roads available to be used in an evacuation;
- In a multi-hazard environment if a regional or local source tsunami was generated by an earthquake which could also produce rockfall and block roads;
- If there was a car crash which meant roads could not be used, which occurred in the 2011 Tōhoku tsunami evacuation (Fraser et al., 2012).

Note that the focus of this analysis was how the roading network may cope with a potential increase in vehicles all evacuating to the same safe zones, which could be achieved by the above scenarios. A rockfall assessment or traffic details including statistics and locations of vehicular crashes have not been used to inform this analysis, however could be used in future research.

The following survey data informed the safe zones for the additional modelling:

- Akaroa – an evacuee reported that a known evacuation centre within Akaroa is at the local school, while an evacuation route was produced heading up Rue Balguerie;
- Little Akaloa – a documented evacuation route travelled through the township (from the origin point) along Chorlton Road to higher ground;
- Okains Bay – an evacuation route travelled inland along Okains Bay Road.

The evacuation dynamics detailed above reported that people travelled beyond the edge of the tsunami evacuation zones, continuing further inland or to higher ground. The safe zones in these modelling scenarios were informed by the evacuation routes (reported by survey respondents) and determined the road segments that the safe zones were placed on. While it is acknowledged that people should evacuate beyond the edge of the evacuation zone to minimise congestion and allow others to evacuate out of the hazard zone, for the purpose of this research the safe zones were chosen to remain at the edge of the tsunami evacuation zone.

4.4 RESULTS

Table 4.3 presents the maximum time required to evacuate each community in the various evacuation scenarios. A key finding presented in Table 4.3 is that for a tsunami evacuation taking place during peak day traffic with an evacuation speed of 50 km/hr, it is estimated by the CASPER model that a maximum of 2.85 minutes are required to reduce tsunami exposure and evacuate these 10 communities. This, however, increased to 4.66 minutes during the same traffic scenario, but when evacuating at a slower speed of 28.1 km/hr.

The results of the modelling where the number of safe zones were decreased can be viewed in Table 4.4. The quickest evacuation time was for Akaroa when evacuating at a speed of 50 km/hr, where the time was 0.80 minutes. The longest evacuation time produced by the model was during the peak night modelling scenario for Okains Bay at a speed of 28.1 km/hr. Here the evacuation cost was 8.88 minutes.

The remainder of this results section is divided into ten sections, one for each study area. Within this, the results have been sub-sectioned into the three primary outputs, with an added section where required for the results of the modelling where the number of safe zones was changed. The results that are presented include:

- *Vehicle density count*. This output represents the number of vehicles on the different road segments, derived from the edgestats output. Because many of the road segments extend further inland and uphill than the location of the safe zones, many of the road density outputs extend along the entire road segment. Lighter colours indicate fewer vehicles, while darker colours indicates a higher number of vehicles;

- *Evacuation cost*. This output is derived from the routes output, this result represents the time required for evacuees to be routed from origin points to safe zones. Yellow represents lower evacuation costs for faster evacuations, while red indicates higher costs and longer travel times;
- *Safe zone distribution*. This result is derived from the routes output and provides a visual and spatial representation of the safe zones evacuees have been routed to. The different colours indicate the distribution of where evacuees originated from and the safe zones they have been directed to by the routing algorithm.

At the beginning of each section a map is presented which provides spatial reference of the communities including location within New Zealand and street names. Examples of the evacuation modelling results can be viewed within each section, with further results in Appendix H.

Table 4.3: Maximum evacuation cost for each community for the different scenarios. This represents the time required to evacuate all of the origin points in each scenario to safe zones.

	Scenario					
	Normal Traffic		Peak Day Traffic		Peak Night Traffic	
Community	50 km/hr	28.1 km/hr	50 km/hr	28.1 km/hr	50 km/hr	28.1 km/hr
Akaroa	0.75 minutes	1.33 minutes	0.75 minutes	1.33 minutes	0.75 minutes	1.33 minutes
Birdlings Flat	2.85 minutes	2.93 minutes	2.85 minutes	2.93 minutes		
Cass & Corsair Bay	0.26 minutes	0.45 minutes	0.34 minutes	0.59 minutes		
Duvachelle	1.05 minutes	1.86 minutes	1.22 minutes	2.17 minutes	1.23 minutes	2.19 minutes
Little Akaloa	0.65 minutes	1.15 minutes	0.72 minutes	1.28 minutes		
Okains Bay	1.53 minutes	2.72 minutes	2.62 minutes	4.66 minutes	2.64 minutes	4.69 minutes
Pigeon Bay	1.52 minutes	2.71 minutes	1.82 minutes	3.23 minutes	1.75 minutes	3.11 minutes
Takamatua Bay & Robinsons Bay	1.16 minutes	2.06 minutes	1.16 minutes	2.06 minutes	1.16 minutes	2.06 minutes
Tumbledown Bay, Te Oka Bay and Magnet Bay	0.36 minutes	0.64 minutes	0.36 minutes	0.64 minutes		
Wainui	1.04 minutes	1.84 minutes	1.25 minutes	2.21 minutes		

Table 4.4: Maximum evacuation cost for each community for the different scenarios. In these examples the number of safe zones has been decreased.

	Scenario					
	Normal Traffic		Peak Day Traffic		Peak Night Traffic	
Community	50 km/hr	28.1 km/hr	50 km/hr	28.1 km/hr	50 km/hr	28.1 km/hr
Akaroa	0.80 minutes	1.42 minutes	1.07 minutes	1.89 minutes	0.84 minutes	1.50 minutes
Little Akaloa	1.25 minutes	2.21 minutes	1.27 minutes	2.25 minutes		
Okains Bay	4.96 minutes	8.82 minutes	4.98 minutes	8.85 minutes	4.99 minutes	8.88 minutes
Wainui	2.10 minutes	3.74 minutes	2.13 minutes	3.78 minutes		

4.4.1 Akaroa

Figure 4.9 shows the location and streets of the Akaroa township.

Evacuation modelling was completed for peak day, peak night and normal traffic scenarios for Akaroa. Overall results showed no change in the evacuation time for the two speeds within the three scenarios. As shown in Table 4.3, the maximum time required to evacuate the vehicles at the three scenarios with a travel speed of 50 km/hr was 0.75 minutes, while for an evacuation speed of 28.1 km/hr it was 1.33 minutes.

Figure 4.9: Street names of Akaroa within the tsunami evacuation zone. Included in the map is an inset with the location of Akaroa within Banks Peninsula and New Zealand.

4.4.1.1 Vehicle Density Count

Vehicle density count in the normal traffic scenario showed little variation in the densities assigned to roads, with most roads assigned between zero and 20 vehicles. In all of the evacuation scenarios Rue Balguerie was assigned a high vehicle density count, ranging from 90 during the peak night scenario, to 30 during the normal resident, and 216 during the peak day scenario. Variations in the number and spatial distribution of evacuees changed the vehicle density count for some roads. For example, a segment of Rue Jolie changed from having five vehicles travel along it during the normal traffic scenario to 45 and 56 during the peak night and day scenarios respectively. Similar changes were seen along Bruce Terrace which increased from 13 vehicles during the normal traffic scenario, to 73 at night, and 86 during the peak day scenario. Figure 4.10 presents an example of the vehicle density count results.

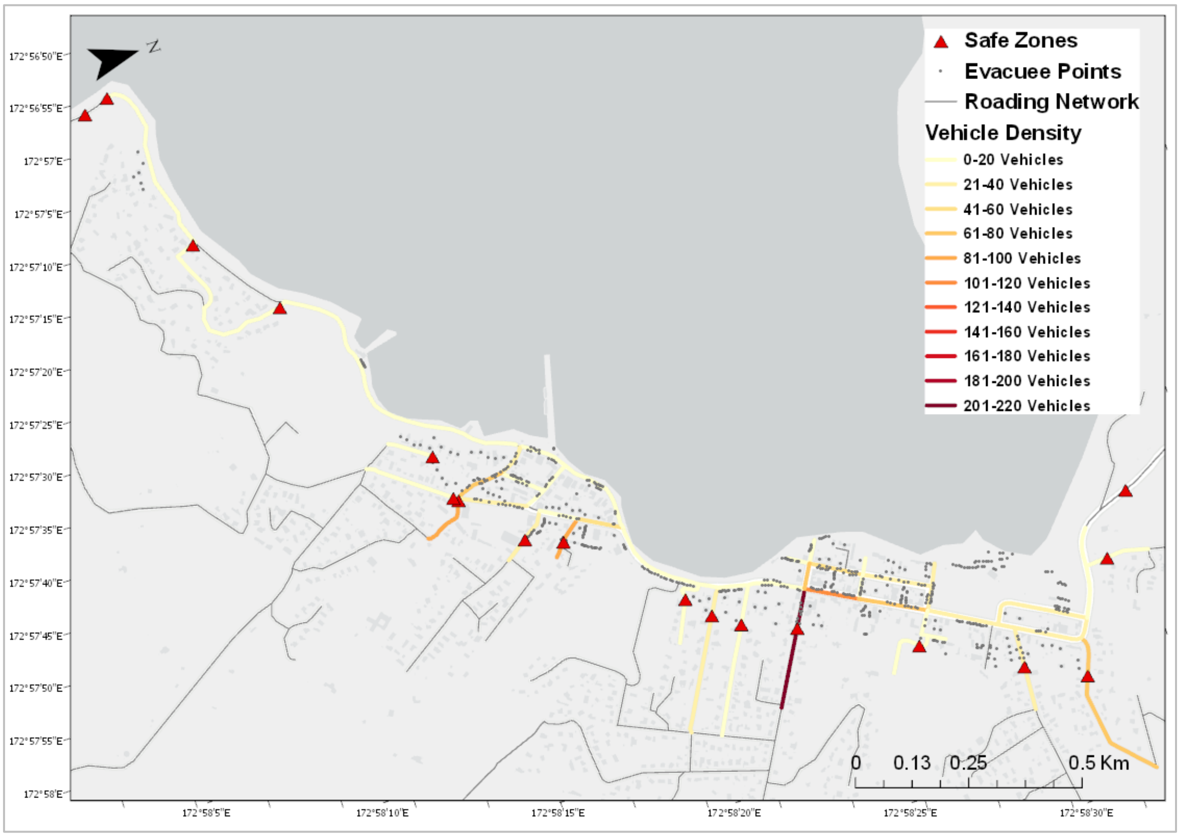

Figure 4.10: Vehicle density count results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.1.2 Evacuation Cost

Many of the evacuees had a higher evacuation cost when modelled evacuating at a slower speed of 28.1 km/hr, compared to evacuating at 50 km/hr. An example of these costs can be viewed below in Figure 4.11. This was particularly noted for evacuees around the Akaroa waterfront including Beach Road, where a section of the road had an increased evacuation cost from between 0.70-0.75 minutes during the 50 km/hr speed scenarios, to between 1.23-1.33 minutes for the scenarios modelled at 28.1 km/hr. In some areas of Akaroa, evacuees had minor changes in their evacuation cost when comparing the two travel speeds. For example the evacuation cost for those travelling along Aubrey Street South during the peak day traffic scenario increased from a 0.06-1.11 minutes when evacuating at 50 km/hr, to 0.09-1.19 minutes when evacuating at 28.1 km/hr.

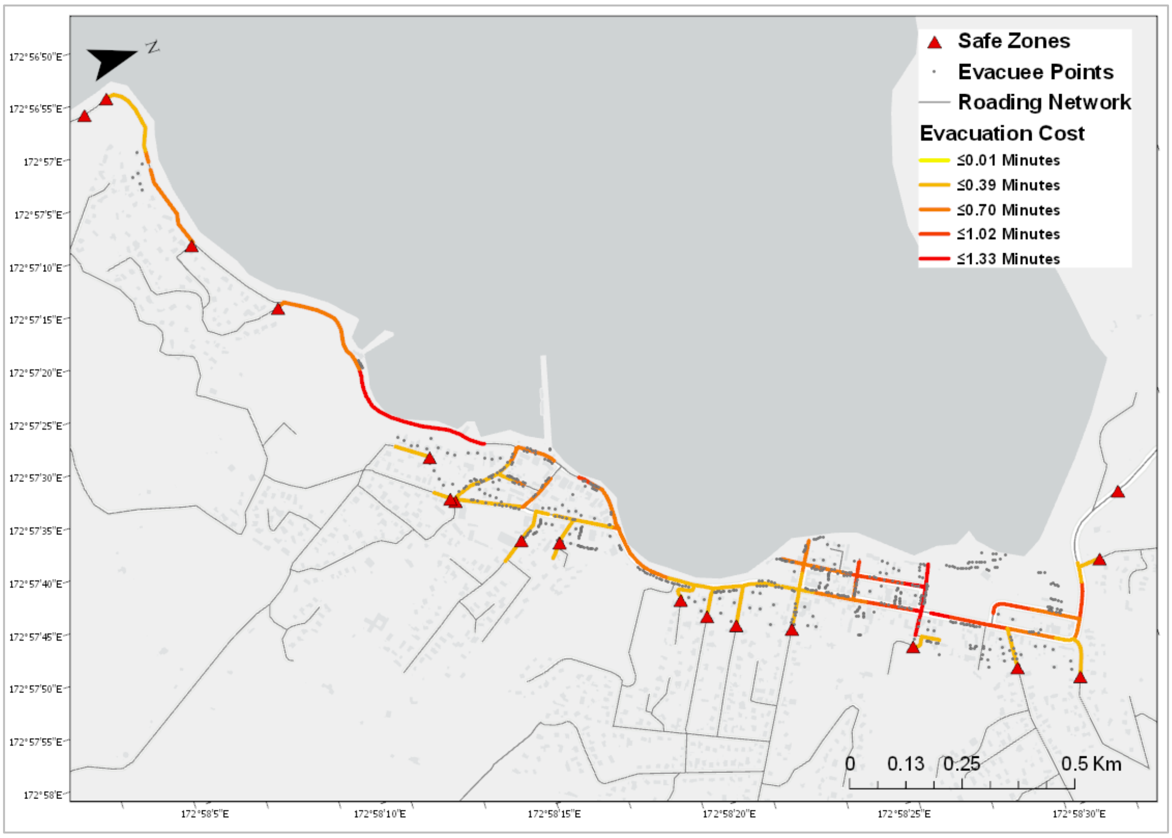

Figure 4.11: Evacuation cost results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

In all modelling scenarios, evacuees on Aubrey Street South and Bruce Terrace had the shortest evacuation costs. Evacuees evacuating from and to Beach Road, and from Rue Jolie, Rue Brittan, and Rue Lavaud to Rue Balguerie had the highest evacuation costs in all scenarios.

4.4.1.3 Safe Zone Distribution

The increase in traffic during the peak day scenario, along with the spatial location of the vehicles, resulted in an additional safe zone utilised in this evacuation modelling. This was the safe zone on Coach Road, which had 12 vehicles directed to it. In all modelling scenarios, the safe zone on Rue Balguerie was most commonly used (Figure 4.12). Some evacuees were not directed to their most direct safe zone (further discussed in Section 4.5.1.3.). For example, evacuees on Rue Brittan were approximately 80 meters from the safe zone on Rue Pompallier, however, had an evacuation journey of 400 meters to reach the safe zone on Rue Balguerie.

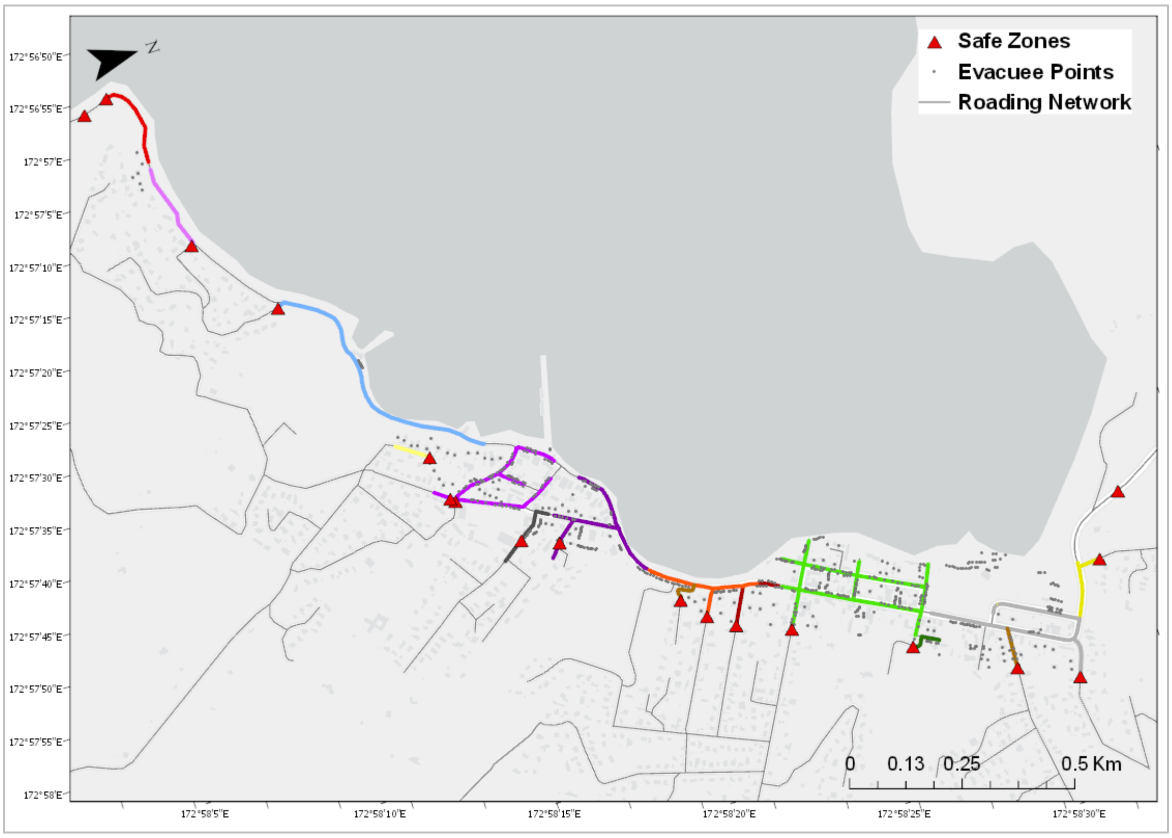

Figure 4.12: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.1.4 Reduction in Safe Zones

In the initial modelling for Akaroa, 18 safe zones were input into the CASPER algorithm. Further modelling was conducted for Akaroa, where the number of safe zones was reduced to four. Two of the safe zones chosen reflected answers in the evacuation behaviour survey (Section 4.3.1.3.1). An additional safe zone was selected on State Highway 75, at the entrance to Akaroa, representing the transient visitors who may not know the area and may attempt to return to Christchurch in an evacuation event. The final safe zone was chosen on Hempleman Drive.

Compared to the original evacuation modelling for Akaroa, the revised modelling had an increase in the overall evacuation time for all scenarios. Despite the overall evacuation time increasing, for all scenarios it remained less than 2 minutes (Table 4.4).

In all modelling scenarios, vehicle densities of roads the four safe zones were on increased compared to the results in Section 4.4.1.1, with the largest increases evident during the peak day modelling scenarios. For example, Rue Balguerie increased from 43 vehicles during the normal resident scenario, to 110 at peak night, and 296 during peak day. The vehicle density count along Bruce Terrace increased from 28 vehicles in the normal resident population modelling scenario, to 92 in the peak night scenario, and further increased during the peak day scenario to 177 vehicles. Similar trends were evident to a lesser extent around the safe zones on State Highway 75 and Beach Road. Increases in vehicle density counts were also evident on roads such as Rue Jolie and Church Street. Some of the roads in Akaroa had consistently low vehicle density count results. For example, a section of Beach Road increased from five vehicles during the peak night and normal modelling, to 12 during peak day. Woodhills Road remained with a vehicle density count of three in all modelling scenarios.

Evacuees that were close to the four safe zones had the shortest evacuation travel times, with those near the Bruce Terrace safe zone having the shortest evacuation costs in all modelling scenarios. Higher evacuation costs were noted for evacuees on Beach Road (on the western side of Akaroa), Walnut Place, Rue Jolie, and Selwyn Ace. This was despite these evacuees having smaller evacuation costs in the initial modelling.

As observed in the initial evacuation modelling for Akaroa, in all evacuation scenarios many evacuees were directed towards the safe zone on Rue Balguerie. For example, in the peak day evacuation models, this safe zone had 282 evacuees directed to it. A higher number of evacuees were routed to the safe zone on Bruce Terrace during the additional modelling when compared to the original modelling. The Hempleman Drive safe zone was the least utilised safe zone in all of the additional modelling scenarios. This safe zone had 11 evacuees directed to it in the normal traffic model, 12 during the peak night model, and 18 during the peak day model.

4.4.2 Birdlings Flat

Figure 4.13 shows the location and streets of the Birdlings Flat township.

Evacuation modelling was simulated for a normal resident population traffic and a peak day traffic scenario for Birdlings Flat. The overall evacuation time required for evacuees to be routed to safe zones did not change in the peak day and normal traffic scenarios at each speed. During the scenarios modelled with an evacuation travel speed of 50 km/hr the maximum evacuation time was 2.85 minutes, while it increased minimally to 2.93 minutes for the scenarios modelled at 28.1 km/hr (Table 4.3).

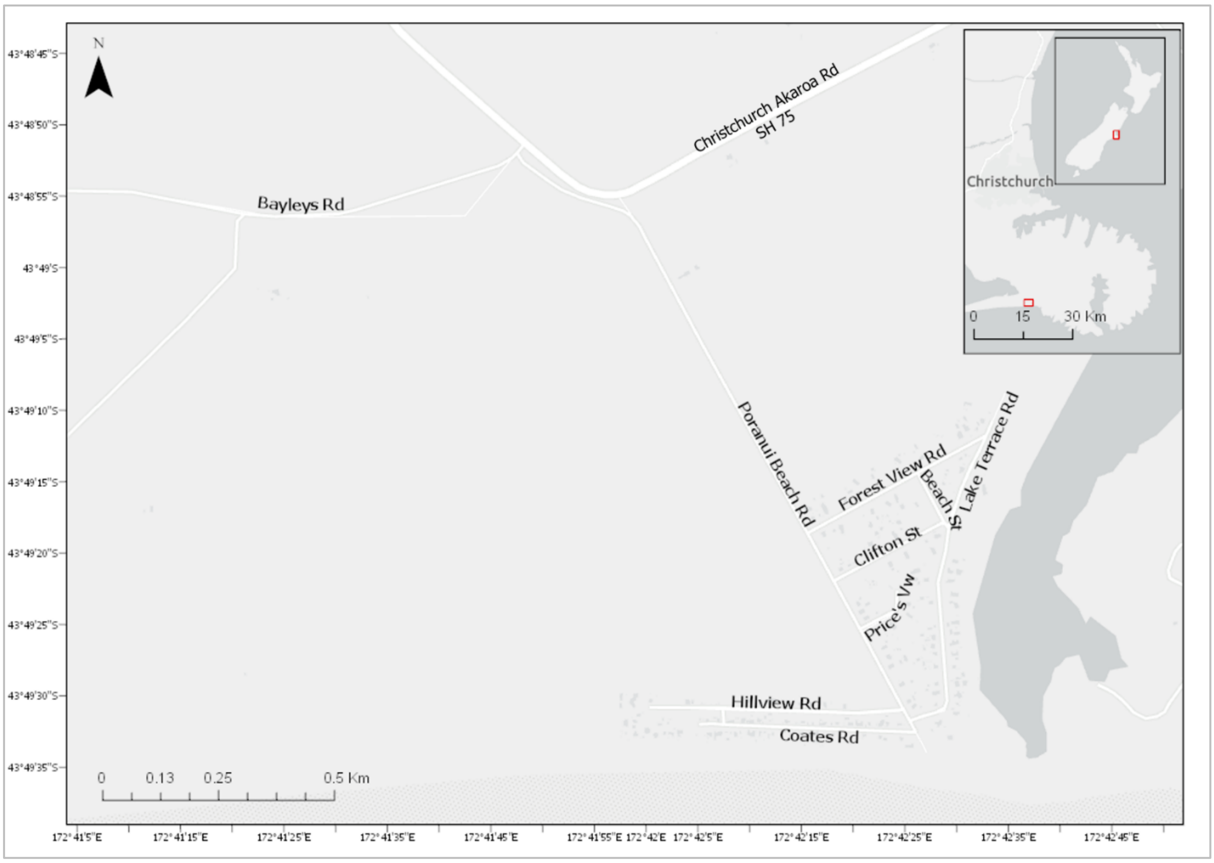

Figure 4.13: Street names of Birdlings Flat within the tsunami evacuation zone. Included in the map is an inset with the location of Birdlings Flat within Banks Peninsula and New Zealand.

4.4.2.1 Vehicle Density Count

Throughout all scenarios the assigned vehicle density did not change much. The only major change that was observed was during the peak day traffic scenarios, where 183 vehicles were directed along Poranui Beach Road (shown in Figure 4.14), decreasing slightly to 157 during the normal traffic scenarios. In all scenarios, very few vehicles were routed along the main road (State Highway 75).

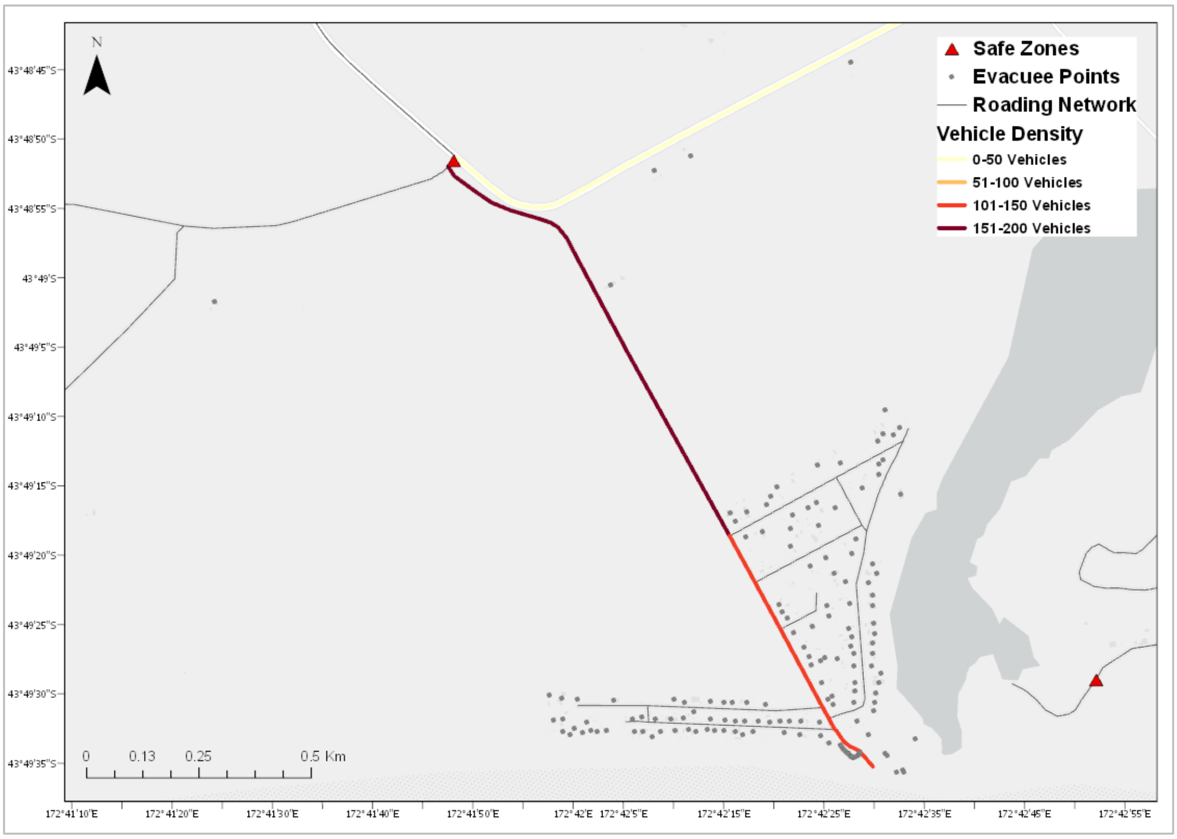

Figure 4.14: Vehicle density count results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.2.2 Evacuation Cost

The longest evacuation cost was for the evacuees leaving from Hill View Road. The evacuation time for these evacuees did not change when using different travel speeds, and was 2.93 minutes during the peak day traffic and 2.85 minutes during the normal resident population scenario. In all scenarios, the evacuees on State Highway 75 and at the top of Poranui Beach Road had the shortest evacuation cost, ranging from 0.61-0.72 minutes for the normal traffic scenario and 0.61-0.74 for the peak traffic scenarios. The evacuation cost for these evacuees did not change when the evacuation speed changed from 50 km/hr to 28.1 km/hr. Figure 4.15 provides an example of the evacuation cost results for Birdlings Flat.

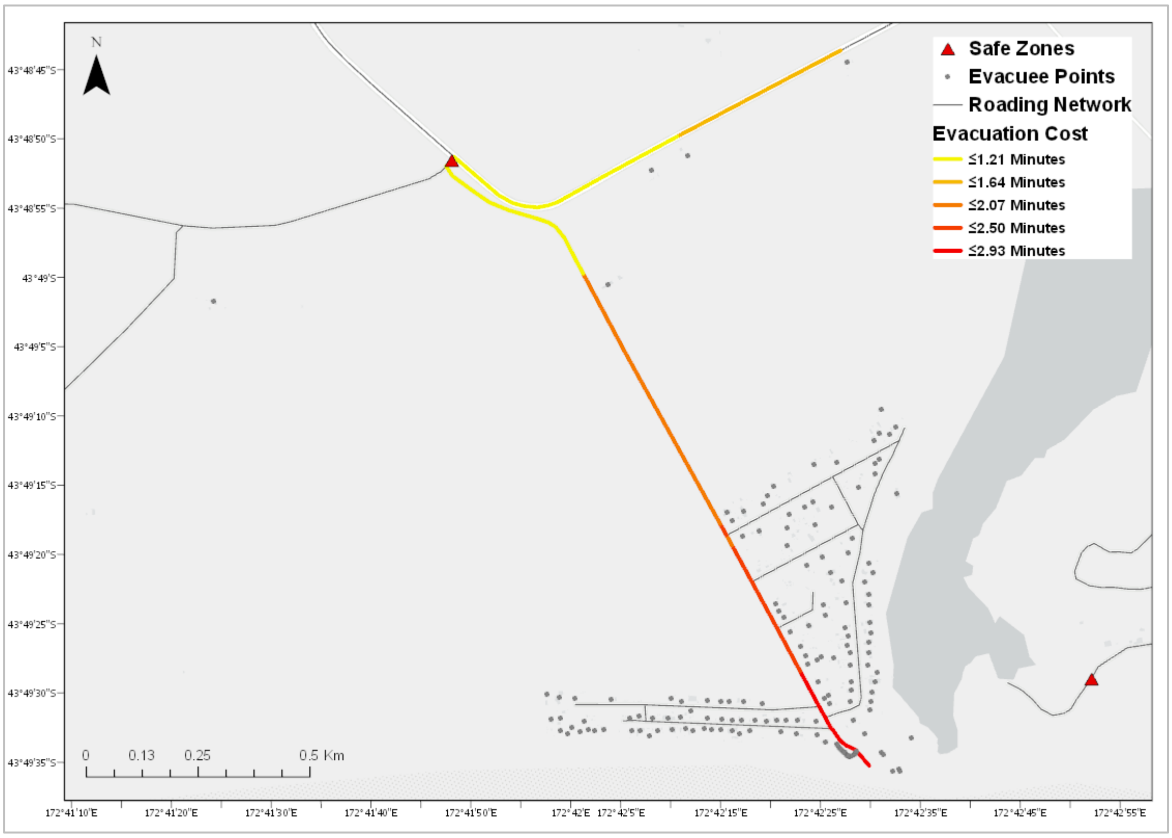

Figure 4.15: Evacuation cost results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.2.3 Safe Zone Distribution

Only one safe zone was utilised during this evacuation, as seen in Figure 4.16. This was the safe zone at the edge of Bayleys Road and State Highway 75.

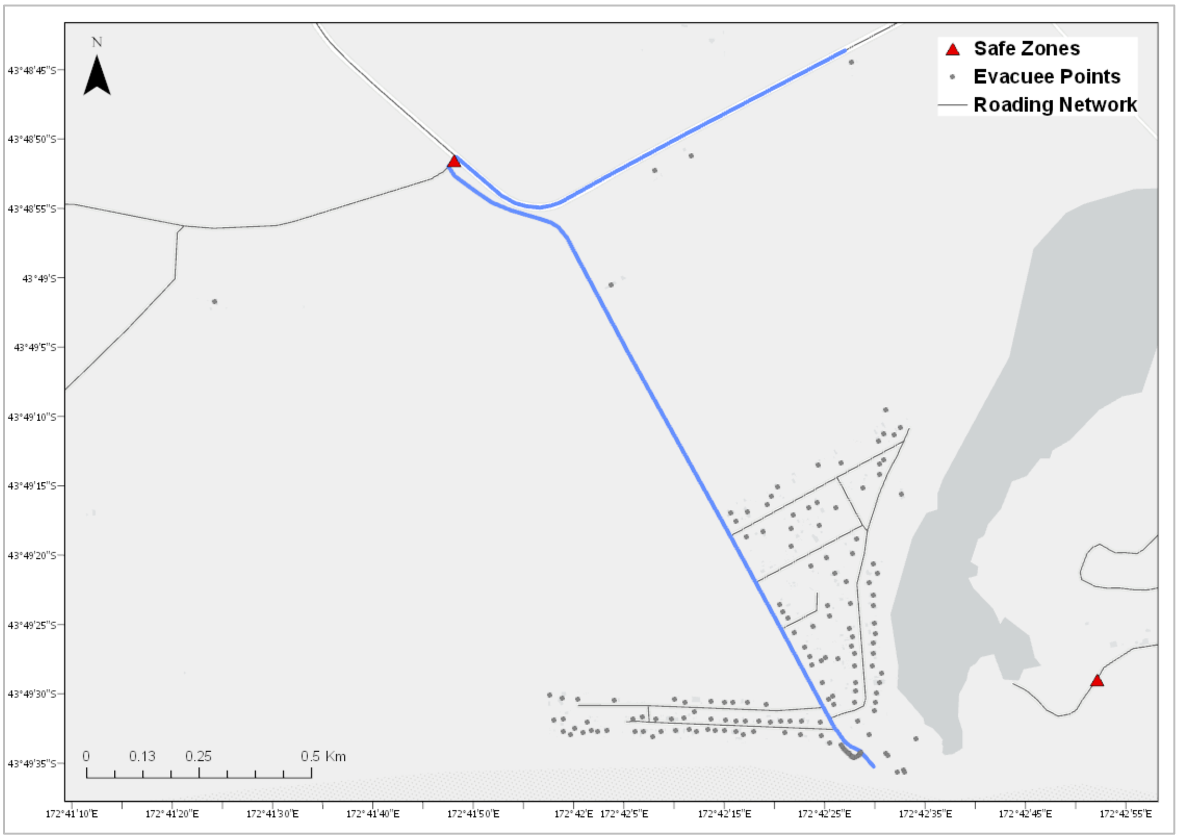

Figure 4.16: Safe zone distribution results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.3 Cass Bay and Corsair Bay

Figure 4.17 shows the location and streets for Cass Bay and Corsair Bay.

Evacuation models representing peak day and normal resident traffic were produced for both Cass Bay and Corsair Bay. Evacuations for these communities were modelled in the same evacuation model based on the low population density and close proximity of these areas. The maximum evacuation time for both peak day and normal traffic scenarios at speeds of 50 km/hr and 28.1 km/hr were all less than one minute (shown in Table 4.3).

Figure 4.17: Street names of Cass Bay and Corsair Bay. Included in the map is an inset with the location of Cass Bay and Corsair Bay within Banks Peninsula and New Zealand.

4.4.3.1 Vehicle Density Count

Changes in vehicle density counts were observed along the road segments near the beach carparks where the vehicles were observed during the field visit. The most notable change was in Corsair Bay, where the assigned vehicle density count changed from zero vehicles during the normal traffic modelling to 65 during the peak day traffic model (peak day shown in Figure 4.18). The vehicle density count along Bayview Place in Cass Bay increased from 10 vehicles during the normal traffic scenario to 31 during the peak traffic.

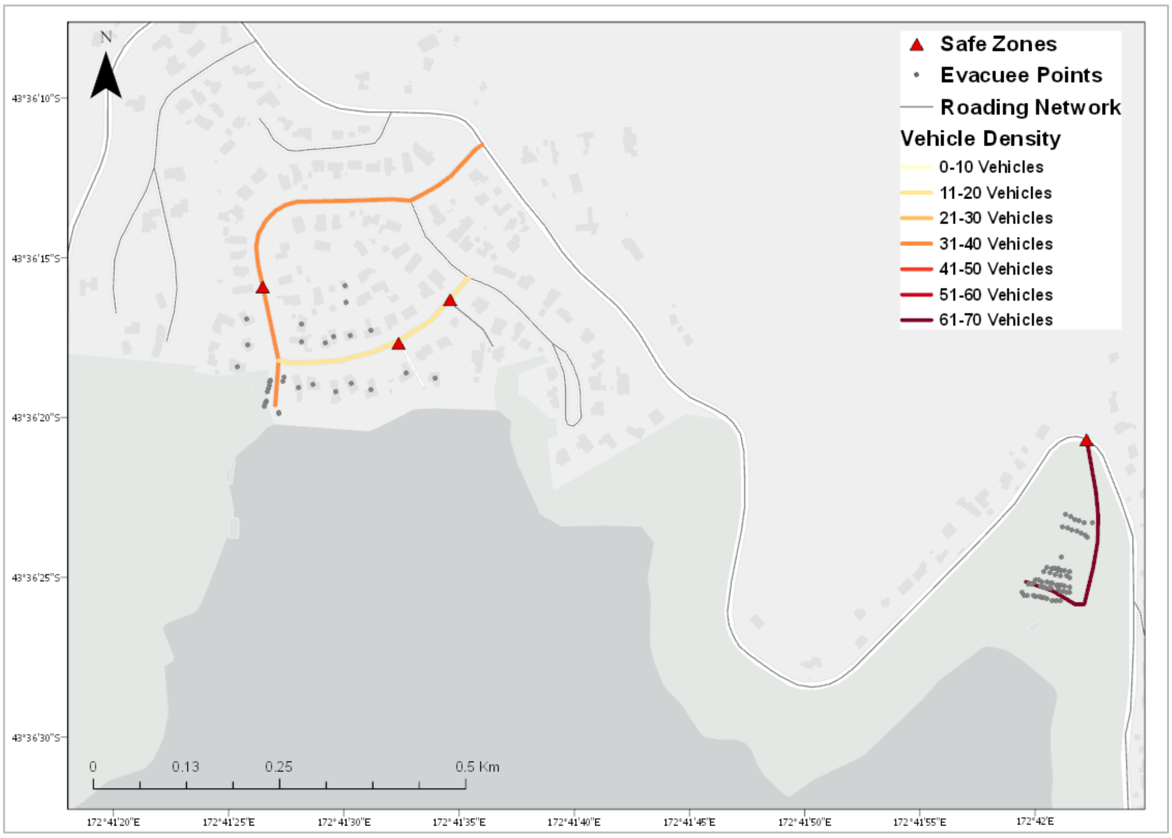

Figure 4.18: Vehicle density count results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.3.2 Evacuation Cost

The highest evacuation cost was for evacuees leaving Corsair Bay during the peak day scenario, with an evacuation speed of 28.1 km/hr (see Figure 4.19). Here, some of the evacuees had an evacuation cost ranging from 0.48-0.59 minutes. The evacuation cost increased in Cass Bay when there were more evacuees and when the evacuation was modelled with a slower travel speed. For example, during the normal traffic evacuation scenario with a travel speed of 50 km/hr, the evacuees along Bayview Place had an evacuation time ranging from 0.17-0.26 minutes, increasing to 0.20-0.29 minutes during the peak day traffic scenario modelled at the same speed.

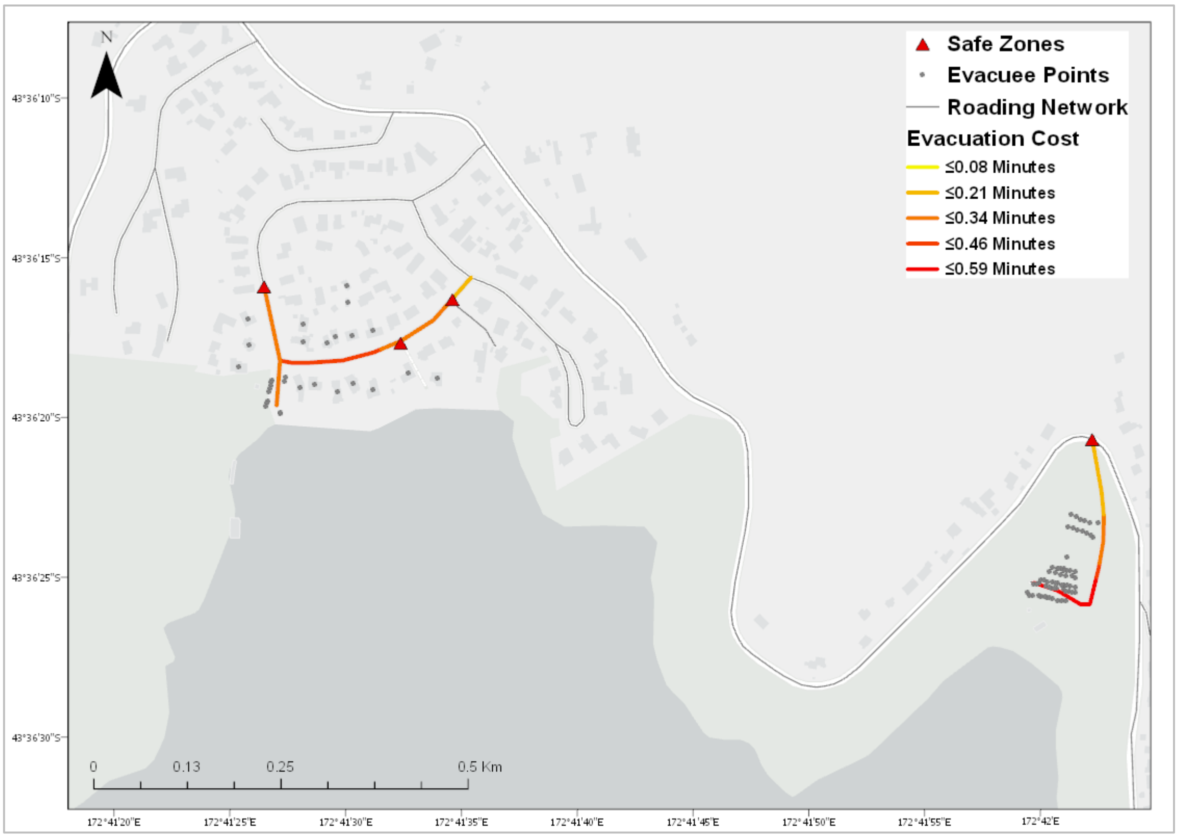

Figure 4.19: Evacuation cost results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1k m/hr during a peak day traffic scenario.

4.4.3.3 Safe Zone Distribution Density

The distribution of evacuees to the safe zones is shown in Figure 4.20. Evacuees at Corsair Bay were directed to the single safe zone in this area. In Cass Bay the evacuees were distributed between three safe zones.

Figure 4.20: Safe zone distribution results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.4 Duvauchelle

Figure 4.21 shows the location and streets of the Duvauchelle township.

Evacuation modelling was completed for peak day, peak night, and normal resident traffic scenarios in Duvauchelle. Shown in Table 4.3, the maximum evacuation time ranged from a 1.05 minutes (normal resident traffic, 50 km/hr) to 2.19 minutes (peak night traffic, 28.1 km/hr).

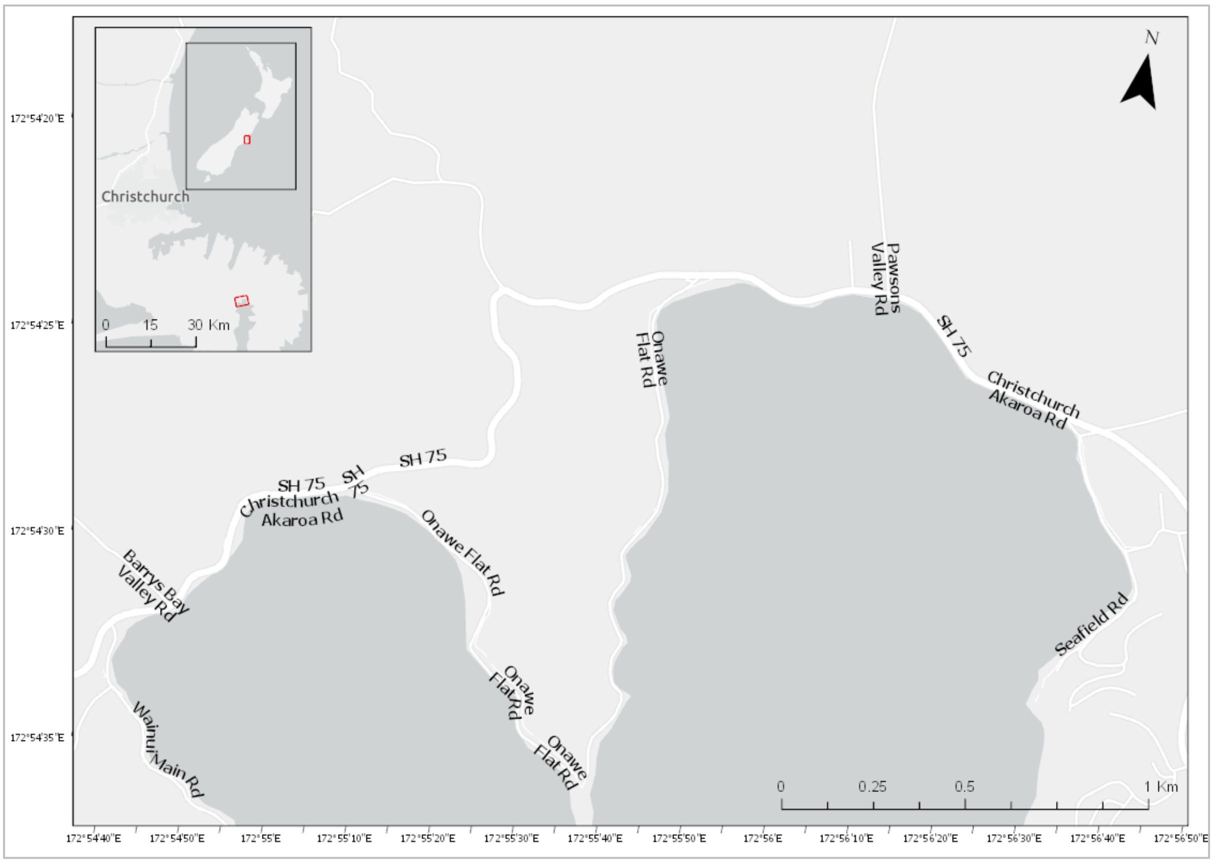

Figure 4.21: Street names of Duvauchelle within the tsunami evacuation zone. Included in the map is an inset with the location of Duvauchelle within Banks Peninsula and New Zealand.

4.4.4.1 Vehicle Density Count

In the normal resident evacuation scenario, the assigned vehicle density count ranged from 1-14 vehicles. Many of the vehicle density counts increased in the peak day and peak night traffic scenarios. State Highway 75 (from Pawsons Valley Road to Seafield Road) was assigned a vehicle density count of 13 in the normal traffic evacuation simulations, but increased to 57 during the peak day traffic, and 64 during the peak night traffic scenarios. Onawe Flat Road (towards Duvauchelle Bay) had an increase in vehicle density count in the peak night modelling to 26 vehicles, compared to just eight during the peak day and normal traffic scenarios. The most noticeable change in these results was around the camp ground. During the normal modelling scenario, eight vehicles were assigned to Seafield Road (near the campground). This increased to 93 and 115 vehicles during the peak day and night traffic modelling scenarios respectively. Figure 4.22 shows the vehicle density count results during a night scenario with an evacuation speed of 28.1 km/hr.

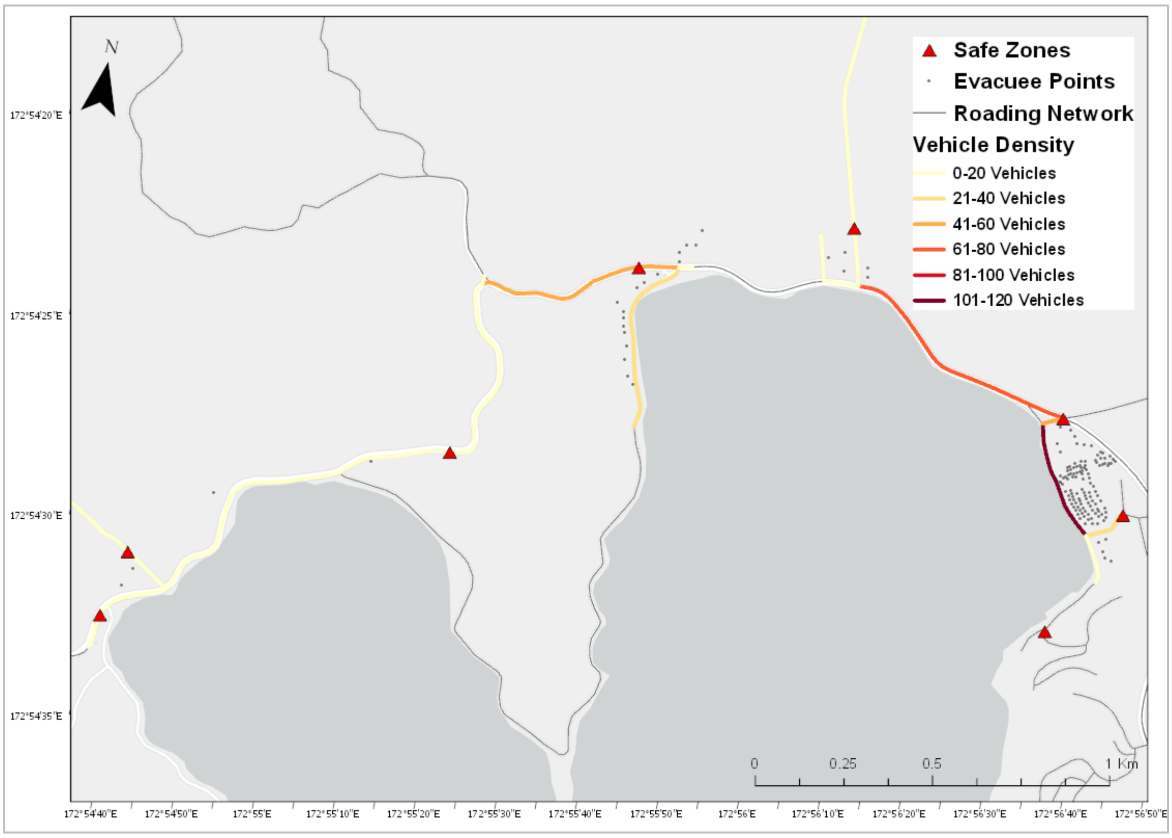

Figure 4.22: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

4.4.4.2 Evacuation Cost

Many evacuees around Duvauchelle experienced only a slight increase in evacuation time for the different modelled scenarios. For example, evacuees around State Highway 75 (near the intersection with Onawe Flat Road in the Duvauchelle Bay) had an evacuation cost of 0.22—0.62 minutes during the three traffic scenarios modelled at 50 km/hr, while this increased to 0.32-1.16 minutes for the same evacuees during the scenarios when the travel speed was decreased to 28.1 km/hr. The highest evacuation cost was for an evacuee from Duvauchelle School Lane who was routed to the safe zone at the intersection of Pipers Valley Road and State Highway 75. The evacuation cost for this evacuee ranged from 1.05 minutes when evacuating at 50 km/hr during normal traffic, to 2.19 minutes when evacuating at a speed of 28.1 km/hr during peak night traffic. An example of an evacuation cost result for Duvauchelle is shown in Figure 4.23.

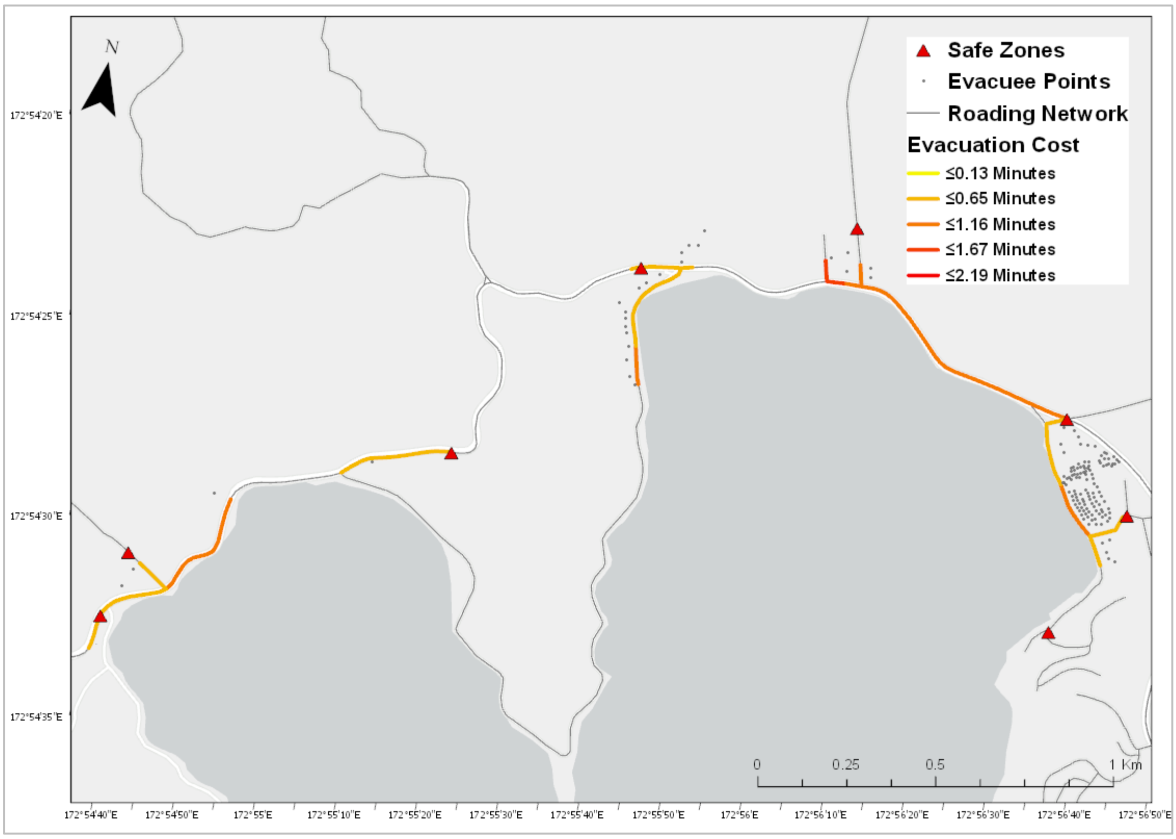

Figure 4.23: Evacuation cost result for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

The evacuation cost for evacuees leaving the Duvauchelle Camp ranged from 0.66-1.34 minutes when the evacuation speed was 28.1 km/hr, and 0.37-0.99 minutes when the speed was 50 km/hr during the peak night traffic scenarios.

4.4.4.3 Safe Zone Distribution

The cluster of vehicles at the camp ground were directed by the routing algorithm to the safe zones on either side of the camp ground. For example, during the peak night scenario, 61 evacuees were routed to the safe zone on Haywards Lane and 64 to the safe zone on Pipers Valley Road (shown in Figure 4.24). This included not only the evacuees from the camp ground, but also the residential and commercial accommodation evacuees.

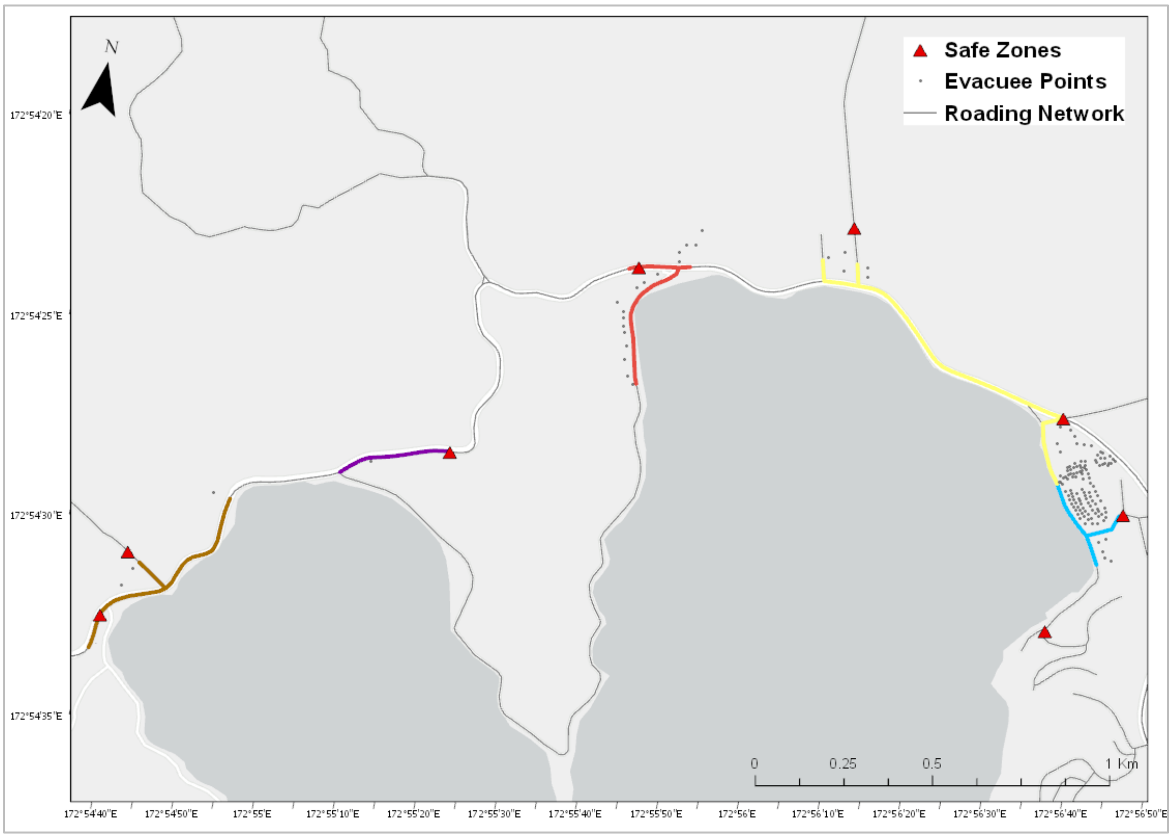

Figure 4.24: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

4.4.5 Little Akaloa

Figure 4.25 shows the location and streets of Little Akaloa.

Evacuation modelling was generated for peak day traffic and normal resident traffic scenarios in Little Akaloa. The addition of congestion in Little Akaloa increased the evacuation time by 0.07 minutes during the peak day traffic scenario and by 0.13 minutes during the normal traffic scenario, as seen in Table 4.3.

Figure 4.25: Street names of Little Akaloa within the tsunami evacuation zone. Included in the map is an inset with the location of Little Akaloa within Banks Peninsula and New Zealand.

4.4.5.1 Vehicle Density Count

During the field visit, vehicles were observed throughout the Little Akaloa community. While only a small number of vehicles were observed, this contributed to a higher vehicle density count on these roads. This was primarily observed on the roads towards the Little Akaloa Bay. Two examples included Chorlton Road and Little Akaloa Road. The vehicle density count of Chorlton Road increased from 18 during the normal traffic modelling, to 27 during the peak day traffic modelling (peak day scenario shown in Figure 4.26). Similar increases were observed along Little Akaloa Road, which increased from 15 during the normal traffic scenario, to 21 in the peak day traffic scenario.

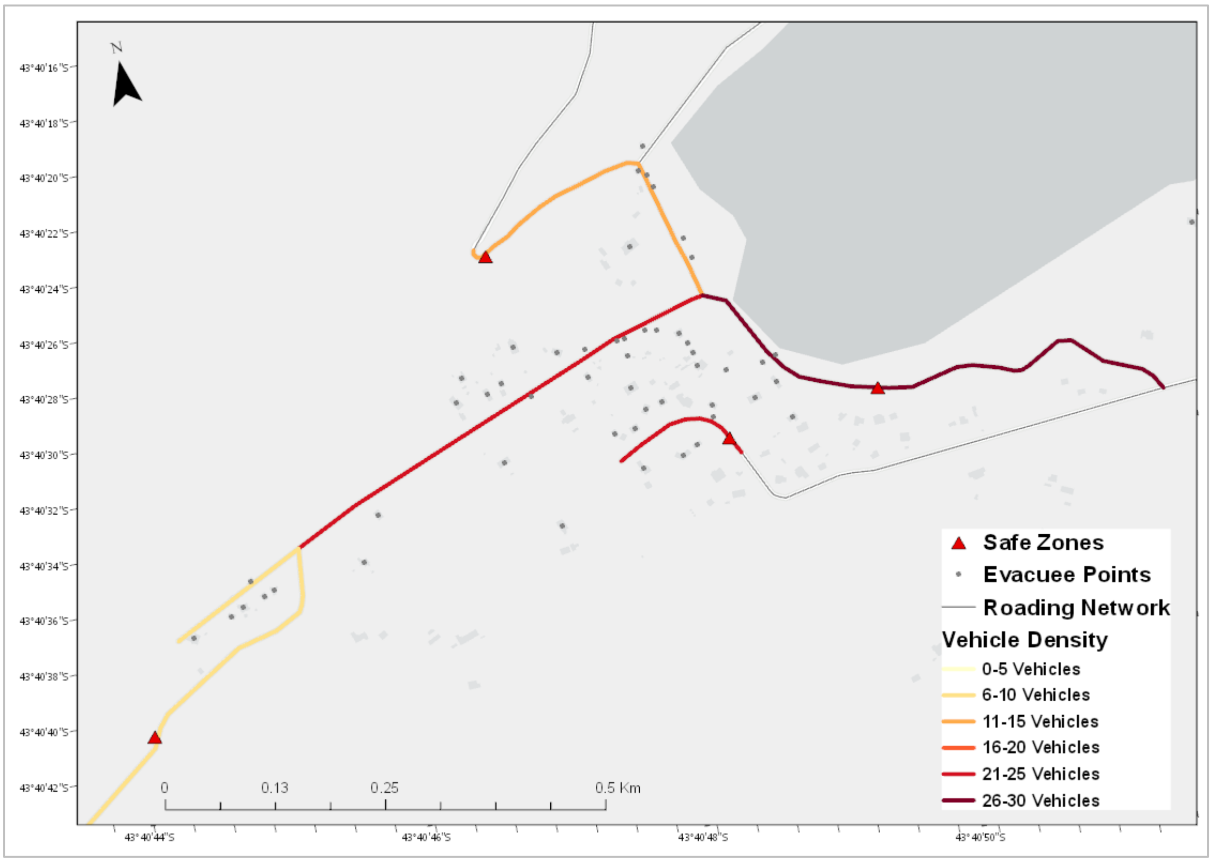

Figure 4.26: Vehicle density count results for Little Akaloa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.5.2 Evacuation Cost

The lowest evacuation cost in Little Akaloa was for evacuees along Lukes Road and some of the evacuees on Chorlton Road. For these evacuees, evacuation times during the normal traffic modelling ranged from 0.10-0.20 minutes (at 50 km/hr) and 0.17-0.35 minutes (at 28.1 km/hr). The highest evacuation travel time for evacuees in Little Akaloa was for those evacuating from Little Akaloa Road to Chorlton Road. Figure 4.27 shows an example of the results for the peak day evacuation cost.

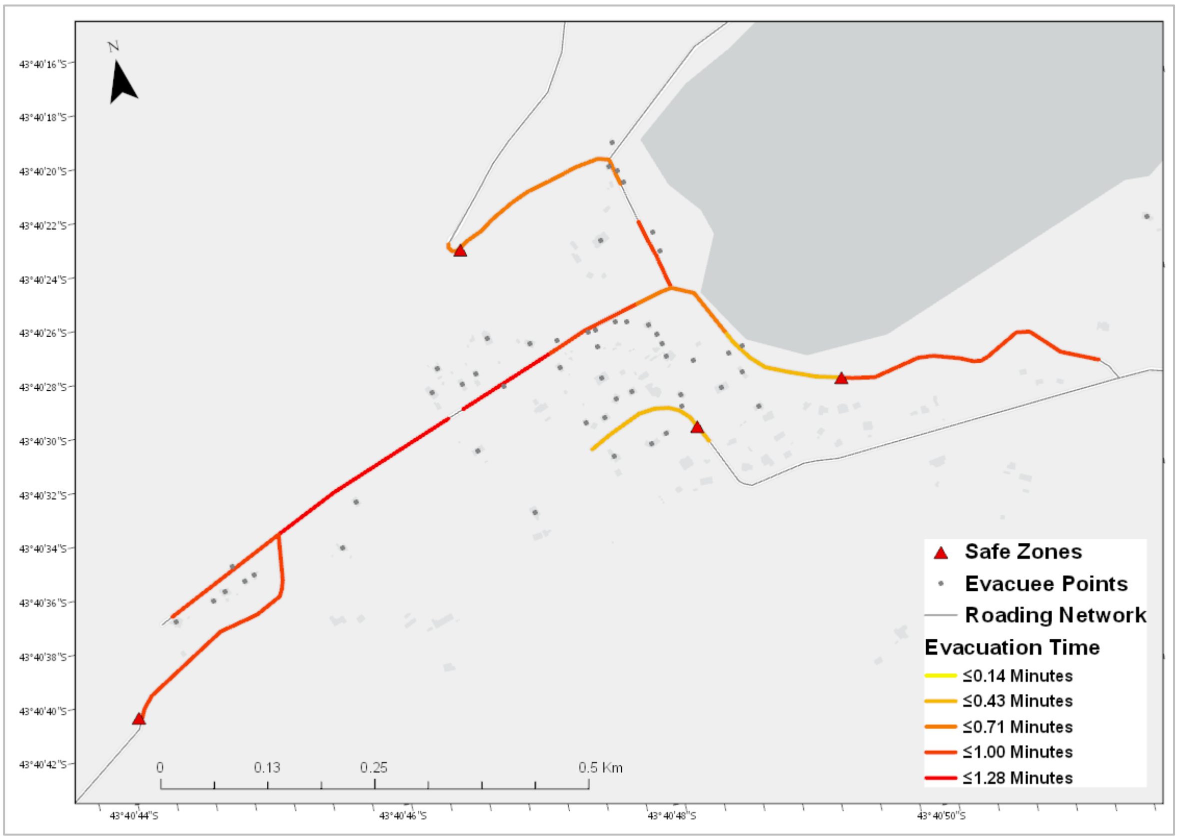

Figure 4.27: Evacuation cost results for Little Akaloa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.5.3 Safe Zone Distribution

Evacuees were routed to their closest safe zone point. While all safe zones were utilised (as evident in Figure 4.28), the majority of the evacuees were routed to the safe zone along Chorlton Road. Twenty-eight of the 52 evacuees were directed to this safe zone during the peak day traffic modelling scenarios, while 19 of the 40 evacuees were directed here during the normal traffic scenarios.

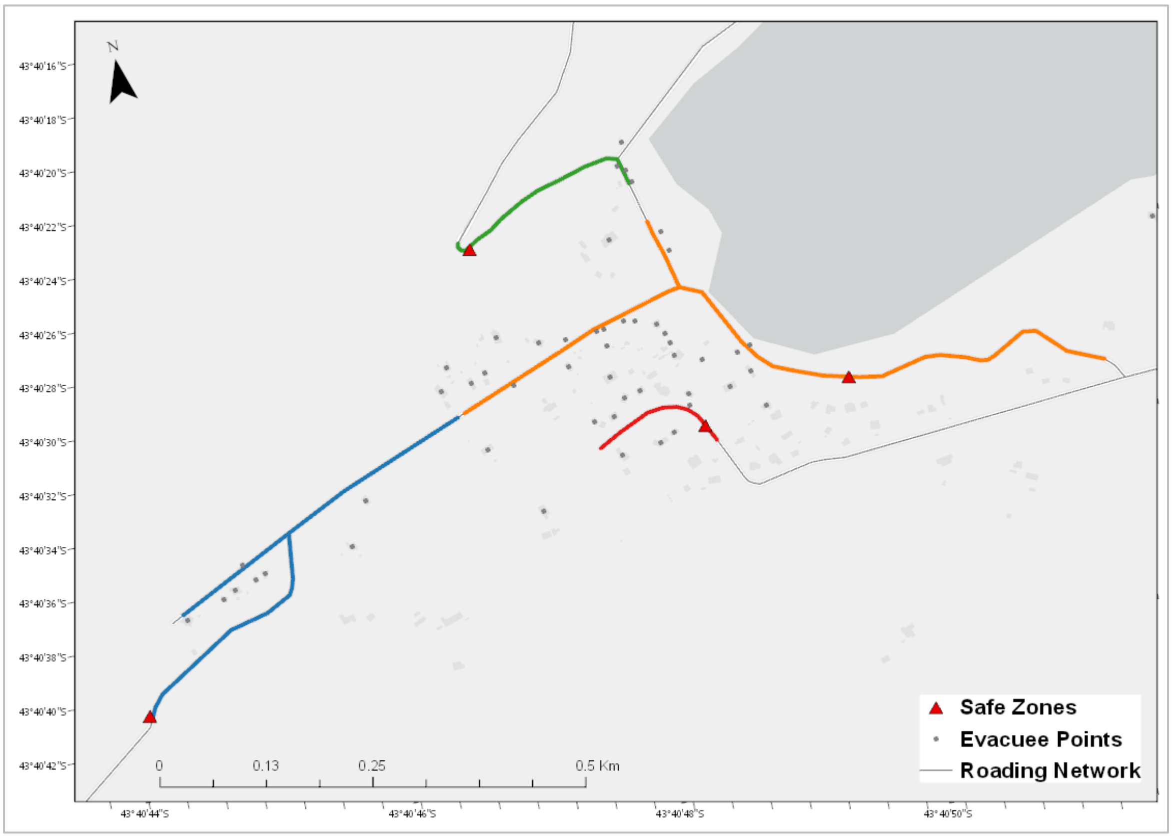

Figure 4.28: Safe zone distribution results for Little Akaloa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.5.4 Reduction in Safe Zones

Additional modelling was undertaken in Little Akaloa, in which the number of safe zones were reduced from four to two. One of the safe zones was informed by the evacuation survey data (explained in Section 4.3.1.3.1), while an additional safe zone was input on Lukes Road.

The overall time required to evacuate Little Akaloa when only utilising two safe zones ranged 1.25-1.27 minutes with a speed of 50 km/hr, and 2.21-2.25 minutes when evacuating at 28.1 km/hr (Table 4.4).

The vehicle density count along Lukes Road remained at 21 during peak day traffic and 19 during normal traffic. There was a decrease in vehicles passing along Decanter Road, from 7 during the additional modelling with peak traffic, to zero vehicles during normal traffic. All other roads in Little Akaloa had an increase in vehicle density.

Evacuation costs increased slightly in the peak day traffic modelling scenarios. For example, in the normal traffic scenario five evacuees along Little Akaloa Road had an evacuation cost ranging from 0.66-0.74 minutes (at 50 km/hr), which increased slightly during the peak day traffic scenario to 0.67-0.75 minutes (at 50 km/hr). The shortest evacuation time was observed for evacuees on Lukes Road and Chorlton Road. The evacuation cost for these evacuees ranged from a minimum of 0.10 minutes to a maximum of 0.22 minutes (peak day and normal traffic at 28.1km/hr). The highest evacuation cost was for those evacuating from Factory Road and the top of Little Akaloa Road.

Vehicles evacuating from Lukes Road were directed to the safe zone on this same road. All other evacuees were directed to the safe zone on Chorlton Road, which during the peak day traffic modelling had 41 evacuees, decreasing to 30 evacuees during the normal traffic modelling.

4.4.6 Okains Bay

Figure 4.29 shows the location and streets of Okains Bay.

Evacuation modelling was completed for peak day, peak night and normal resident traffic scenarios in Okains Bay. As shown in Table 4.3, the evacuation time ranged from 1.53 minutes (normal traffic), to 4.69 minutes (peak night traffic).

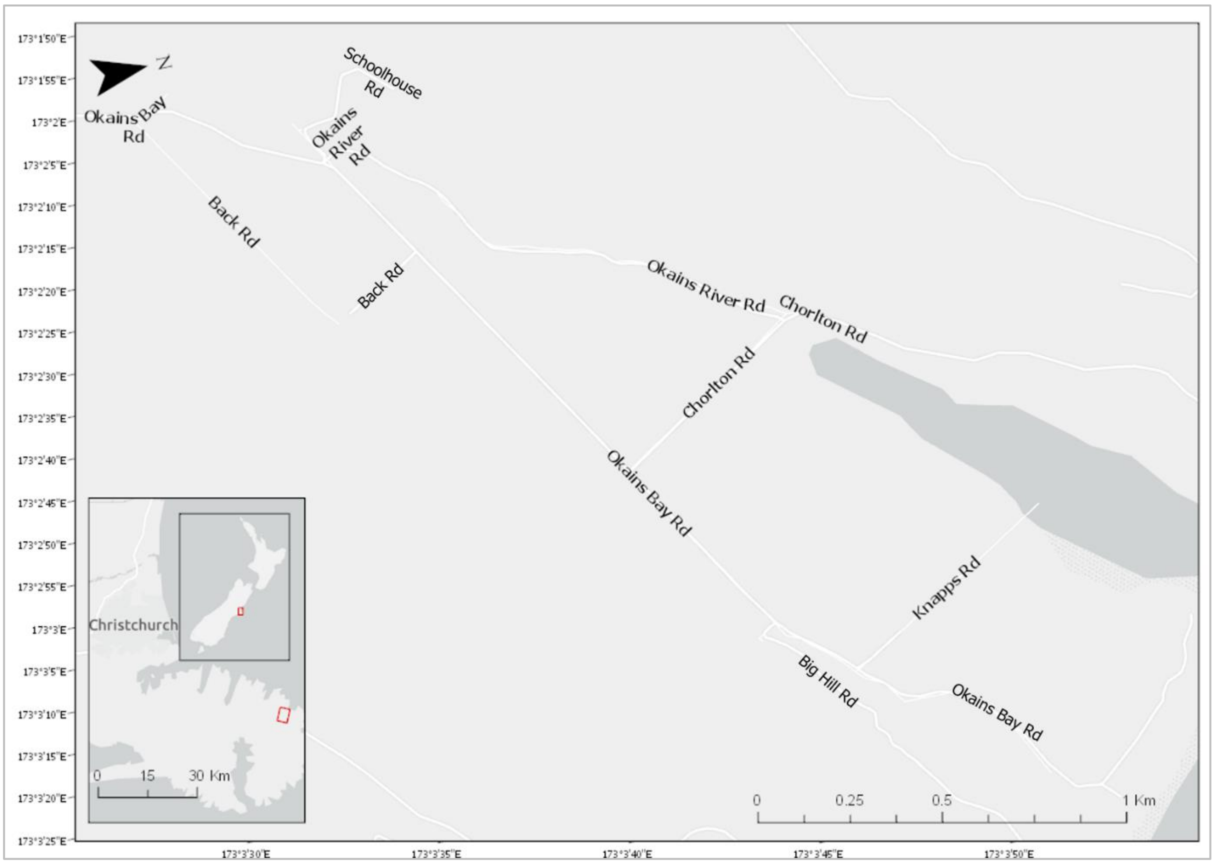

Figure 4.29: Street names of Okains Bay within the tsunami evacuation zone. Included in the map is an inset with the location of Okains Bay within Banks Peninsula and New Zealand.

4.4.6.1 Vehicle Density Count

Many roads in Okains Bay did not have a change in vehicle density count between the three modelling scenarios. Exceptions to this included Chorlton Road which increased from six vehicles during the peak day and normal traffic scenarios, to 10 during the peak night modelling; Okains Bay Road (towards the campground) which increased from three vehicles during the normal traffic scenario, to 127 during the night traffic scenario; and Big Hill Road which increased from 19 vehicles during the normal traffic modelling, to 147 during the peak night traffic scenario. Figure 4.30 shows an example of the vehicle density count results for Okains Bay.

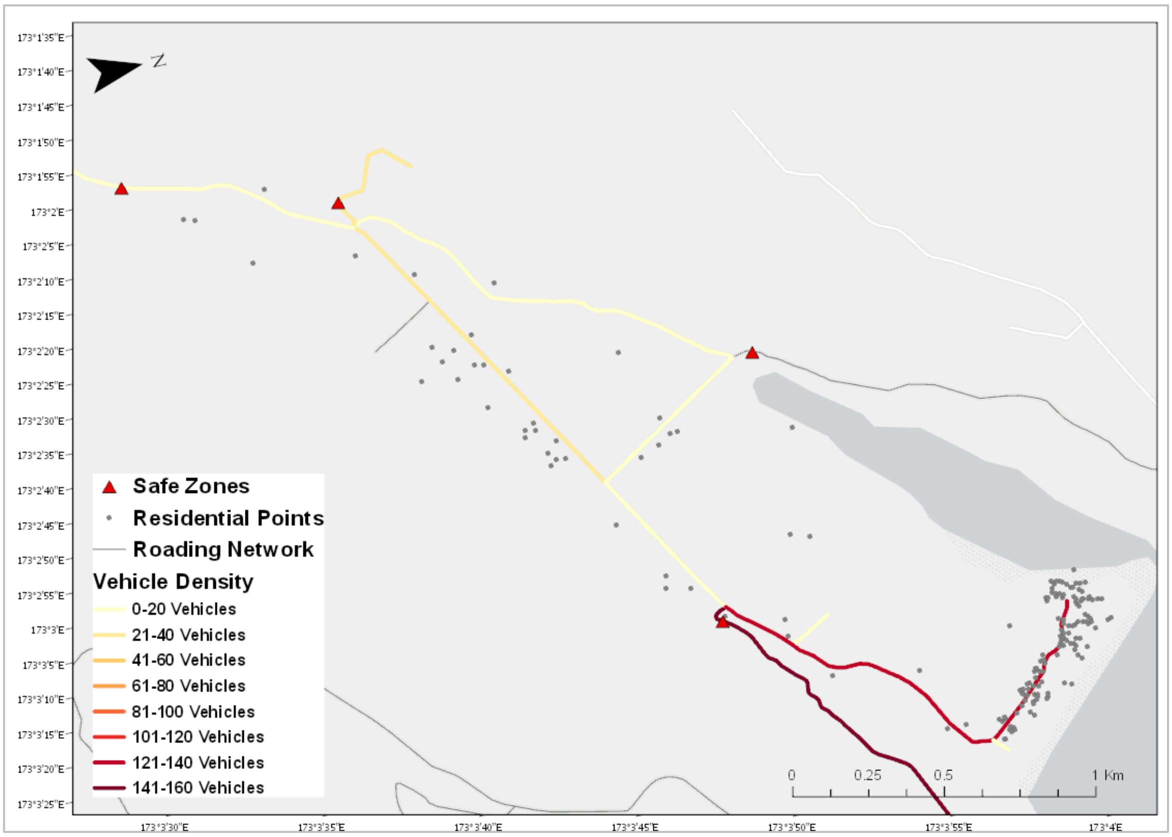

Figure 4.30: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

4.4.6.2 Evacuation Cost

Okains Bay had the highest evacuation cost of all of the communities where evacuations were modelled. This was observed for the modelling simulated with an evacuation speed of 28.1 km/hr, where the peak night cost was 4.67 minutes, while the peak day cost was 4.66 minutes. The highest evacuation cost was for evacuees leaving the camp ground evacuating towards the safe zone on Big Hill Road. For example, during the peak night traffic scenario 32 evacuees had the highest evacuation cost of 4.69 minutes when evacuating at 28.1 km/hr (with this scenario shown in Figure 4.31).

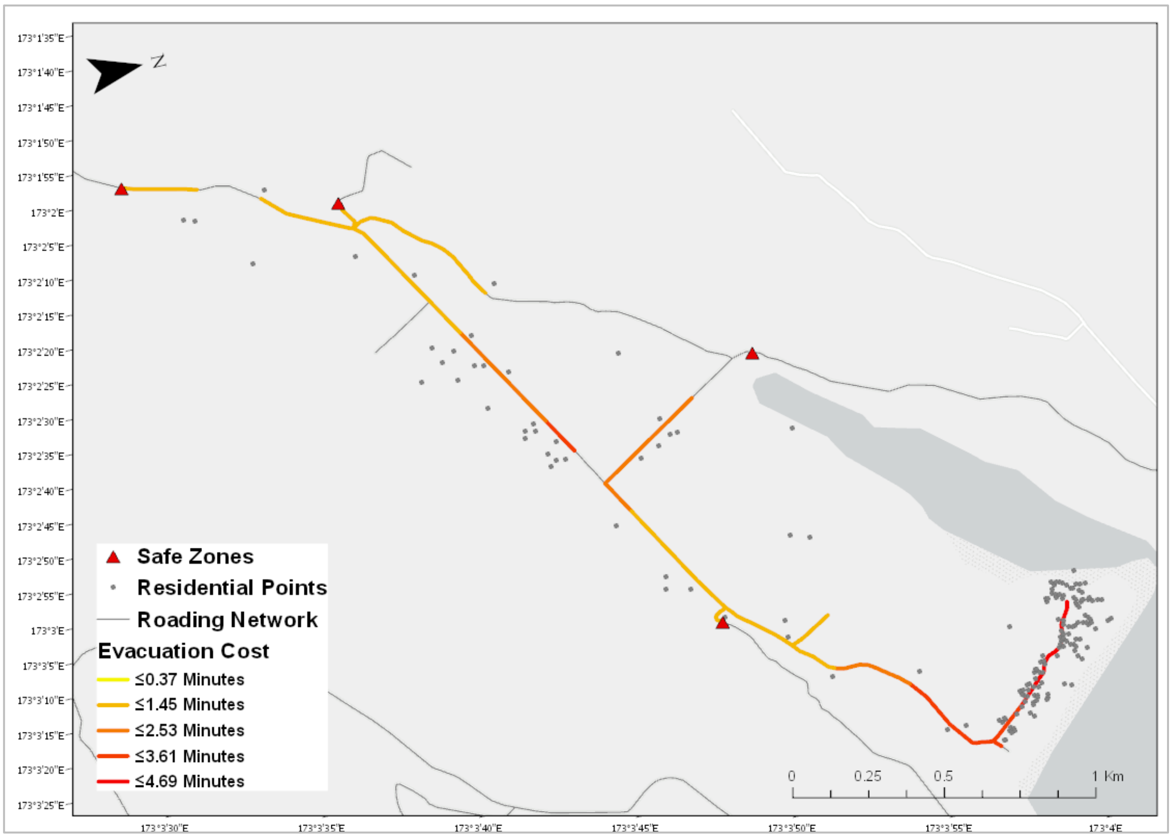

Figure 4.31: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

4.4.6.3 Safe Zone Distribution

During the normal traffic evacuation scenarios, the majority of the evacuees were directed to the safe zone on Schoolhouse Road (24 vehicles), while 18 were directed to Big Hill Road. The distribution of where evacuees were directed to changed in the peak day and night traffic scenarios, in which the safe zone on Big Hill Road had the highest number of evacuees (143 at night and 138 during the day). The distribution of evacuees to safe zones during a peak night modelling scenario is shown in Figure 4.32. The evacuation zone on Chorlton Road was not utilized by the modelling algorithm. This was despite this being the closet safe zone for evacuees on Chorlton Road (approximately 260 meters away) whom were instead directed to the safe zone on Big Hill Road which was approximately 1050 meters away. This will be further discussed in Section 4.5.1.3.

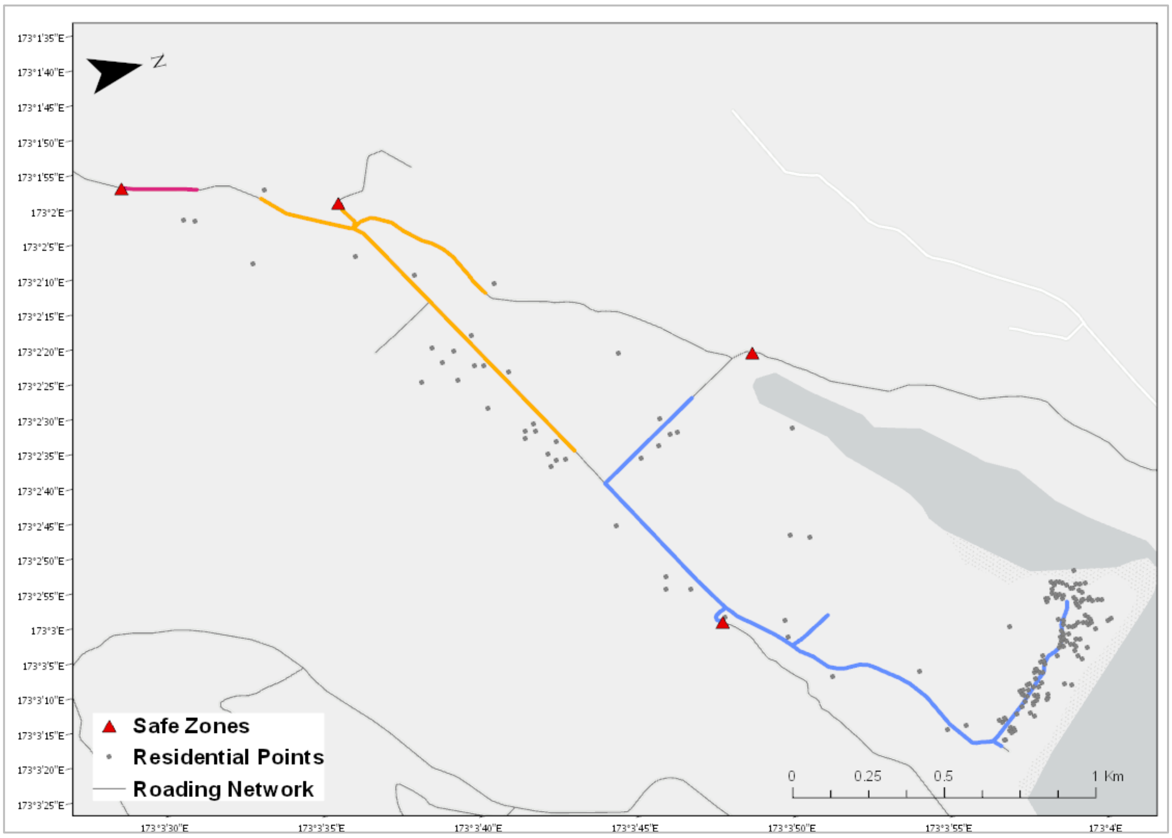

Figure 4.32: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

4.4.6.4 Reduction in Safe Zones

Further modelling was conducted for Okains Bay where the number of safe zones was reduced to two. This included a safe zone on Okains Bay Road, reflecting an evacuation route/road mentioned in the tsunami evacuation survey, while the other point on Big Hill Road was chosen based on its close proximity to the camp ground.

The overall evacuation cost for Okains Bay when only utilising two safe zones ranged from 4.96-4.99 minutes with a speed of 50 km/hr, and 8.82-8.88 minutes when evacuating at 28.1 km/hr. This was an increase from the original modelling, which had a maximum of 4.69 minutes required to evacuate vehicles in this community.

As similarly observed in the initial evacuation modelling for Okains Bay, Big Hill Road and Okains Bay Road leading into the camp ground had the highest vehicle density counts. The removal of some of the safe zones increased the vehicle counts on Big Hill Road to 163 during the peak day traffic scenarios and 171 during the peak night scenarios. The top of Okains Bay Road had a low vehicle density count in all modelling scenarios.

The highest evacuation cost was for evacuees along Okains Bay Road (between Chorlton Road and Back Road). When evacuating at 50 km/hr, these evacuees had an estimated evacuation time of 4.20-4.99 minutes, increasing to 7.46-8.88 minutes when evacuating at a speed of 28.1 km/hr. Two evacuees on Okains Bay Road near the safe zone on this road had the shortest evacuation time. The evacuation time for these evacuees was 0.36 and 0.13 minutes when evacuating at 50 km/hr, and 0.54 and 0.69 minutes at 28.1 km/hr for the three evacuation scenarios.

In all of the modelling scenarios only two evacuees were directed to the safe zone at the top of Okains Bay Road. All other evacuees were routed to the safe zone on Big Hill Road.

4.4.7 Pigeon Bay

Figure 4.33 shows the location and streets of Pigeon Bay.

Evacuation modelling was produced for peak day, peak night and normal resident traffic scenarios in Pigeon Bay. Evacuation costs for Pigeon Bay are shown in Table 4.3. Travelling at an evacuation speed of 50 km/hr, the maximum evacuation time required for vehicles to relocate to safe zones throughout Pigeon Bay increased from 1.52 minutes during normal traffic, to 1.82 minutes during peak day traffic. Using an evacuation speed of 28.1 km/hr, the evacuation time increased from 2.71 minutes for normal traffic, to 3.23 minutes for peak day traffic.

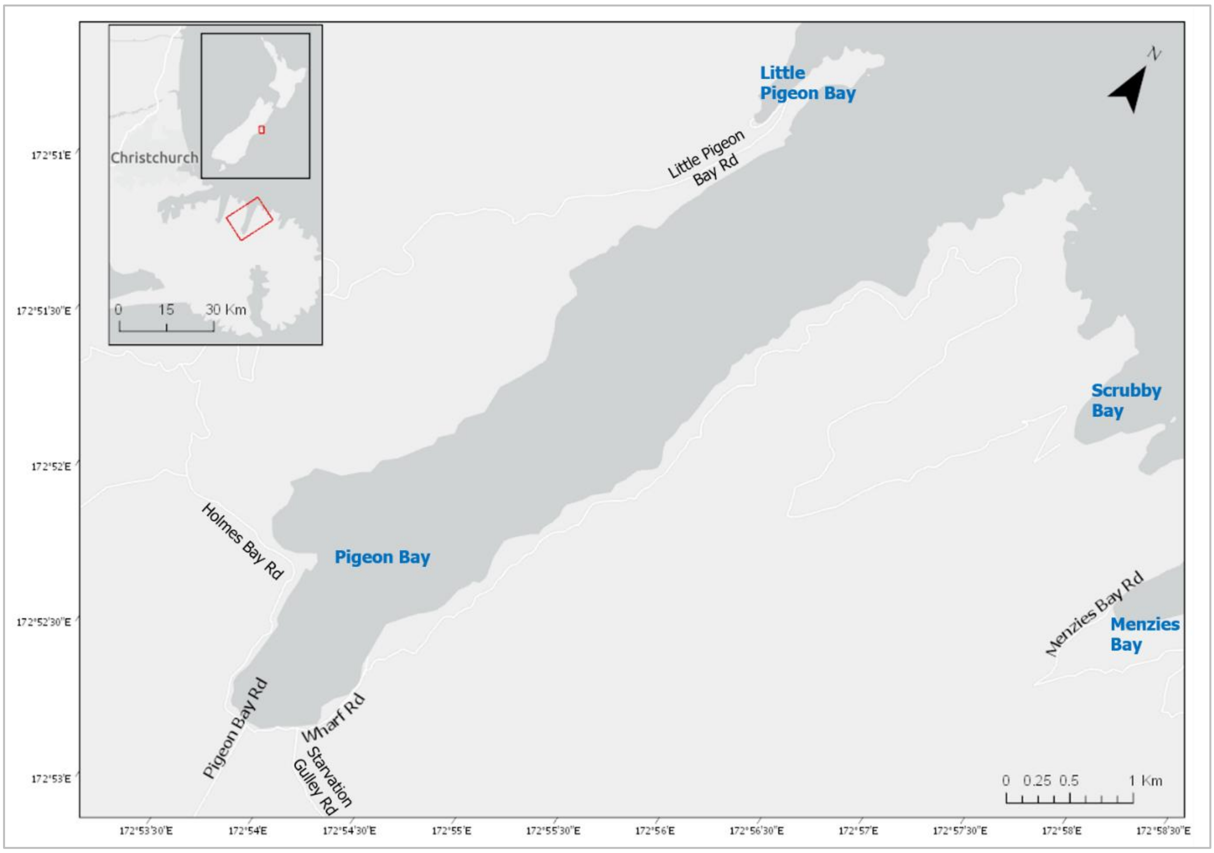

Figure 4.33: Street names of Pigeon Bay. Included in the map is an inset with the location of Pigeon Bay within Banks Peninsula and New Zealand.

4.4.7.1 Vehicle Density Count

The vehicle density count along many of the road segments in Pigeon Bay increased in the peak day and night traffic scenarios. The number of vehicles directed to pass along Wharf Road increased from 34 during the peak night traffic scenarios, to 53 during the peak day traffic scenarios. A similar increase was observed on Starvation Gulley Road where the vehicle density count increased from 13 during the normal modelling, to 63 during the congestion day, and 44 during the peak night modelling. Figure 4.34 shows an example for the vehicle density count results during a peak day scenario.

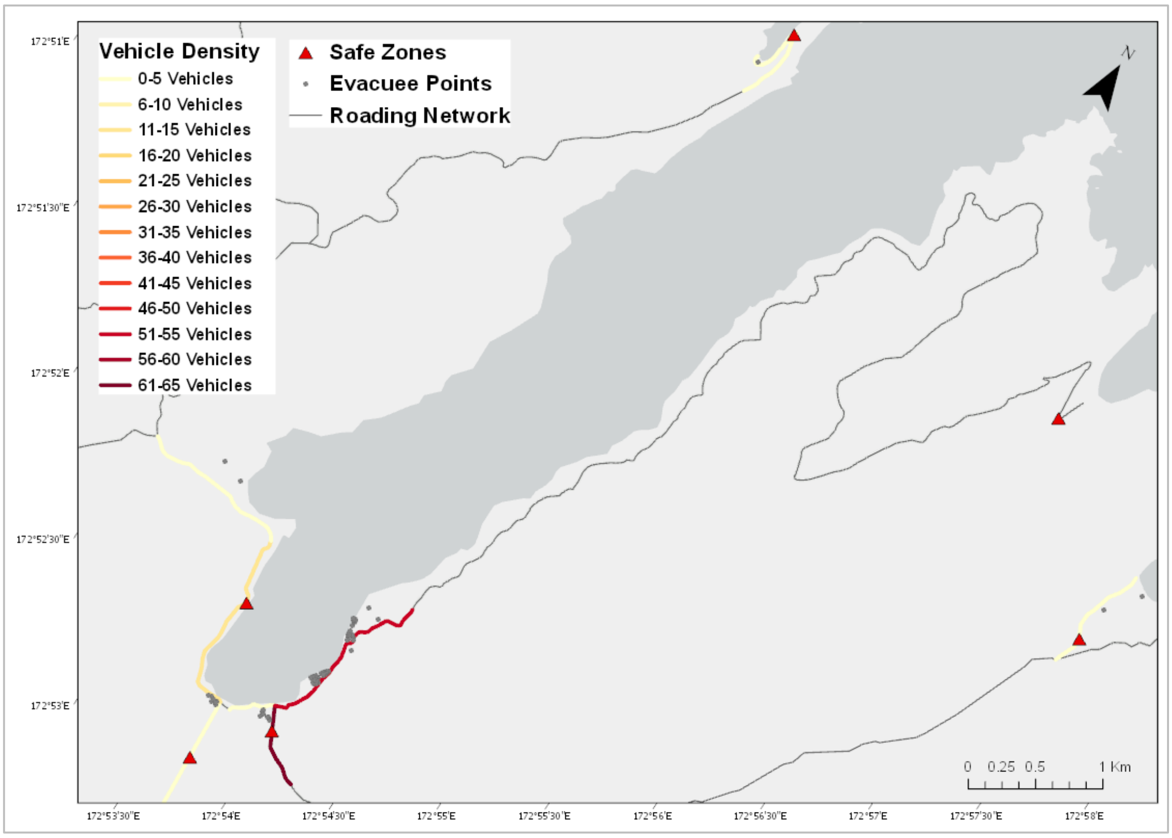

Figure 4.34: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.7.2 Evacuation Cost

Evacuation costs increased for all evacuees during the scenarios modelled with a speed of 28.1 km/hr. Evacuees originating from residential points and the Yacht Club (near the top of Wharf Road) had the highest evacuation cost during the peak day scenario (shown in Figure 4.35). The evacuation cost here ranged from 1.31-1.82 minutes when evacuating at 50 km/hr, to 2.33-3.16 minutes when evacuating at 28.1 km/hr. Evacuees from Scrubby Bay, Little Pigeon Bay, and around the intersection of Wharf Road and Starvation Gulley Road had the quickest evacuation times in all scenarios.

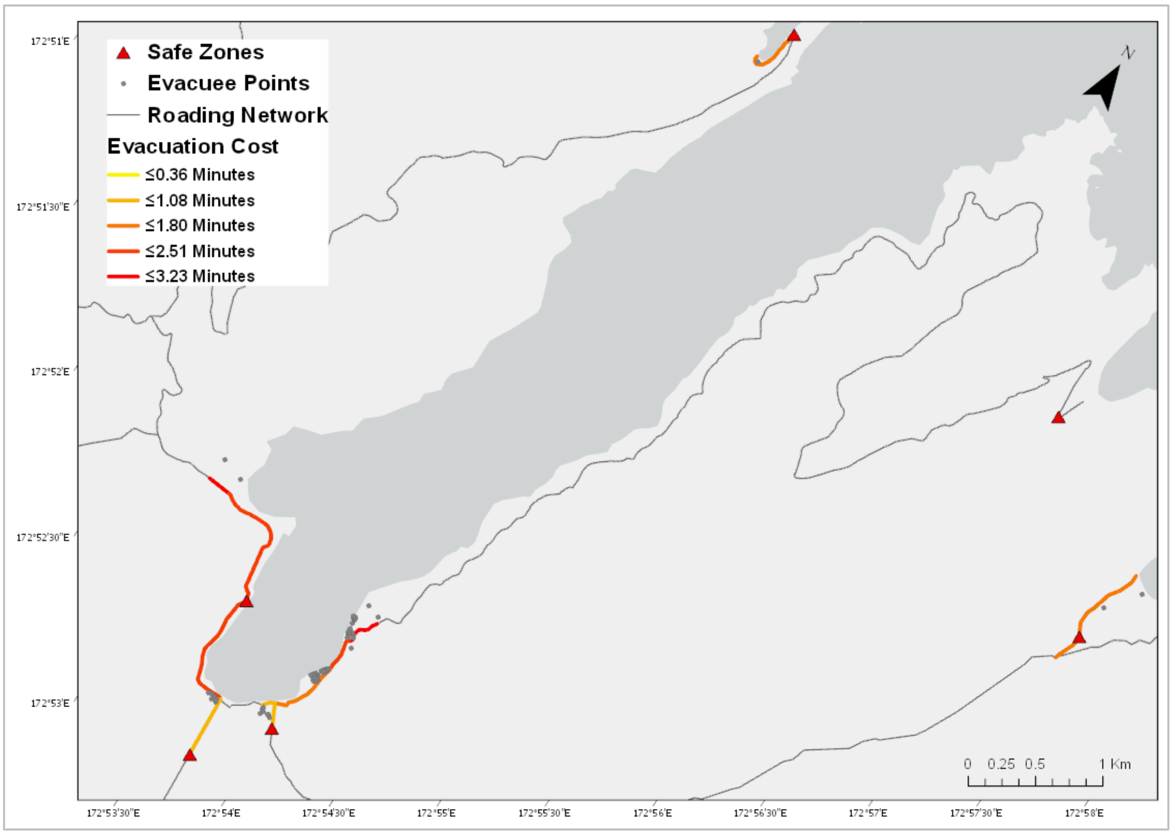

Figure 4.35: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.7.3 Safe Zone Distribution

Evacuees at Little Pigeon Bay, Scrubby Bay, and Menzies Bay (the smaller bays around the north of the Pigeon Bay area) were directed to their closest evacuation safe zone, as seen in Figure 4.36. Some interesting observations were made regarding the distribution of evacuees to safe zones in the peak night traffic results, as evident in Figure 4.36. A cluster of seven evacuees relating to residential points were located on Holmes Bay Road, near the intersection with Pigeon Bay Road. These evacuees were directed approximately 930 meters to a safe zone further along Holmes Bay Road, instead of being routed to the one on Pigeon Bay Road which was approximately 490 meters away. This will be discussed in Section 4.5.1.3.

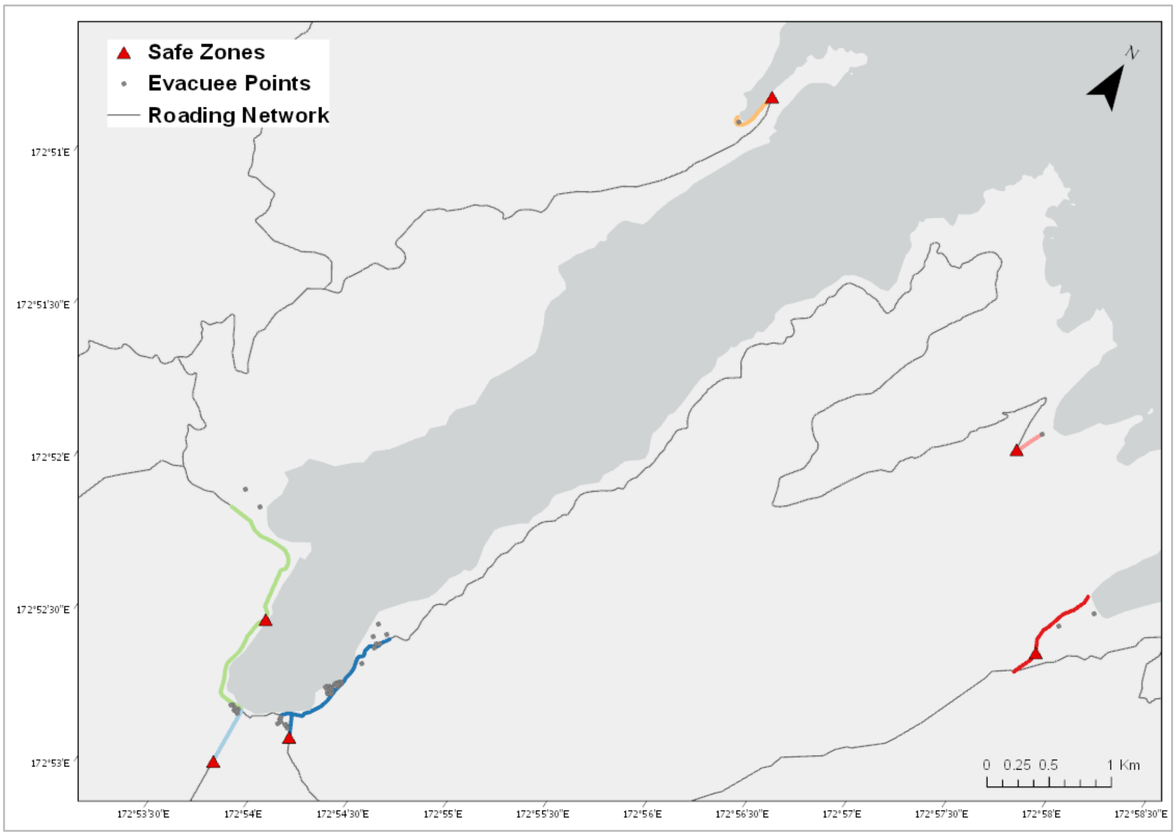

Figure 4.36: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

4.4.8 Takamatua Bay & Robinsons Bay

Figure 4.37 shows the location and streets of Takamatua Bay and Robinson Bay.

Evacuation modelling representing peak day, peak night and normal traffic were produced for both Takamatua Bay and Robinsons Bay. Evacuations for these communities were simulated in the same evacuation model because of their low population density and close proximity. In all three traffic scenarios the maximum evacuation cost was 1.16 minutes when evacuating at a speed of 50 km/hr, increasing to 2.06 minutes for all scenarios when evacuating at 28.1 km/hr (Table 4.3).

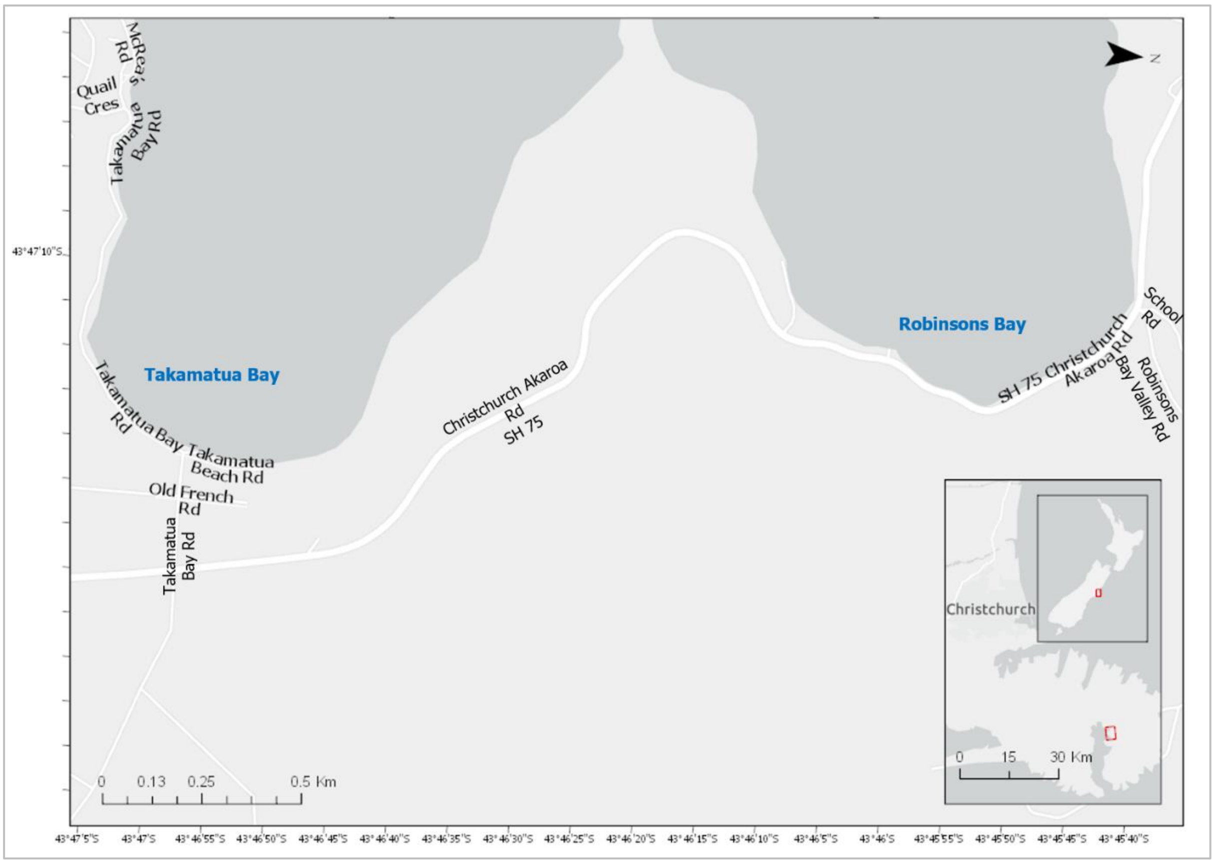

Figure 4.37: Street names of Takamatua Bay and Robinsons Bay. Included in the map is an inset with the location Takamatua Bay and Robinsons Bay within Banks Peninsula and New Zealand.

4.4.8.1 Vehicle Density Count

In all evacuation modelling scenarios, Old French Road had the highest vehicle density count. This changed from 28 vehicles during the normal resident traffic scenario, to 31 in both the peak night and day traffic scenarios. Further vehicle density changes were evident along Takamatua Bay Road (between Takamatua Valley Road and Quail Road), where vehicle count increased from zero to 11 from normal to peak day traffic. Figure 4.38 provides an example of the vehicle density count results during a peak day scenario.

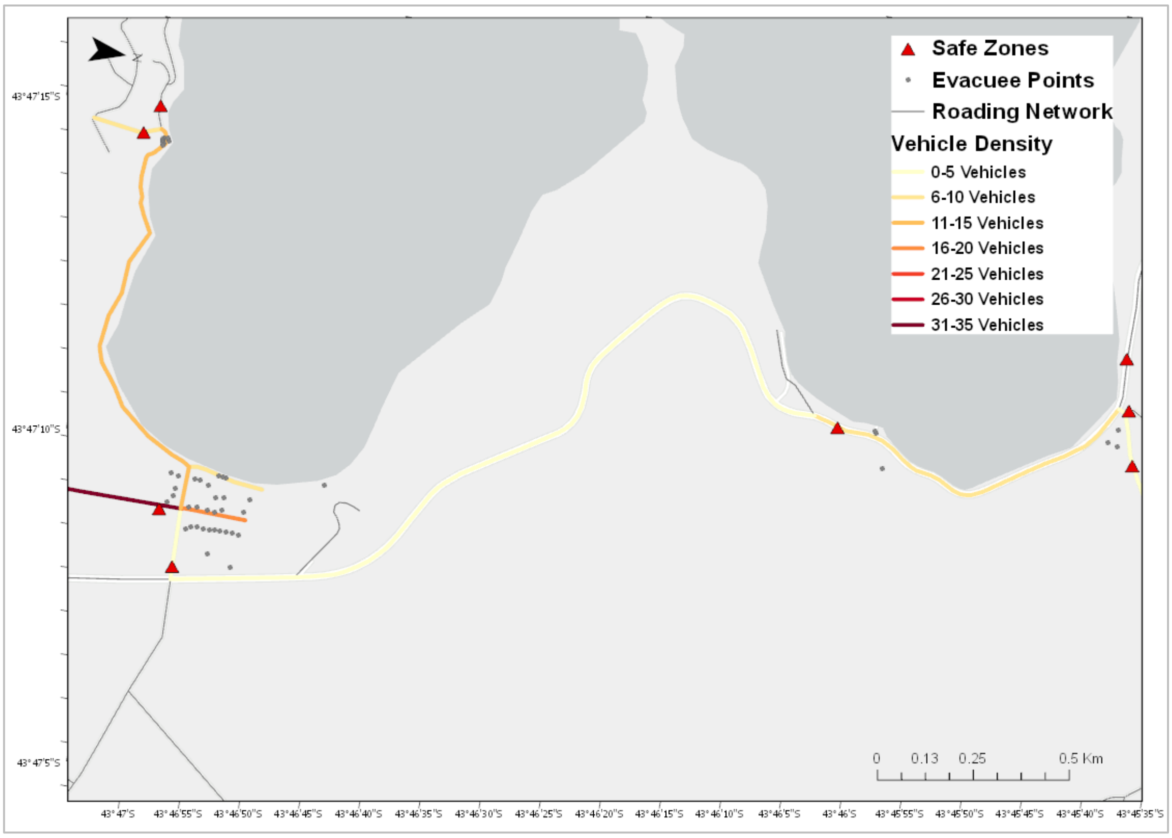

Figure 4.38: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

The assigned vehicle density count for roads around Robinsons Bay did not change throughout the modelling scenarios.

4.4.8.2 Evacuation Cost

Evacuation costs for those in Robinsons Bay were higher than the evacuation costs for other evacuees. In all scenarios when travelling at 50 km/hr the evacuation cost of these evacuees ranged from 1.09-1.16 minutes, and increased to 1.94-2.06 minutes when evacuating at 28.1 km/hr. In all other evacuation modelling results, the evacuation time for the remaining evacuees were much lower, at 0.77 minutes or less for both travel speeds. Evacuees along Takamatua Bay Road had the quickest evacuation time. Figure 4.39 shows an example of the evacuation cost results for Takamatua Bay and Robinsons Bay.

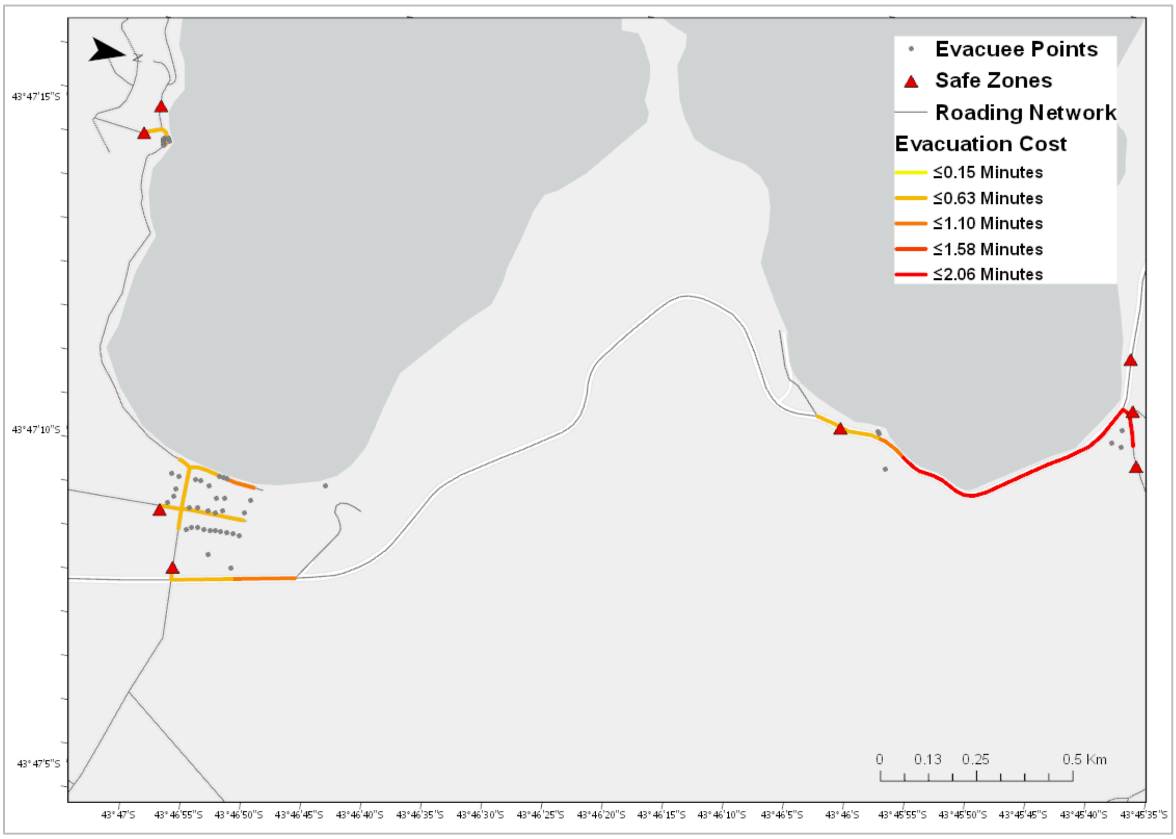

Figure 4.39: Evacuation cost results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.8.3 Safe Zone Distribution

All of the evacuees within the Takamatua township were directed to the safe zone on Old French Road. Very few evacuees were directed to the safe zone on Takamatua Bay Road. Despite there being three safe zones near Robinsons Bay (on Robinsons Bay Valley Road, School Road, and State Highway 75) which was approximately 50 meters away from these evacuees origin points, they were routed by the modelling algorithm to the safe zone further along Robinsons Bay (approximately 960 meters away), as shown in Figure 4.40. This will be further discussed in Section 4.5.1.3.

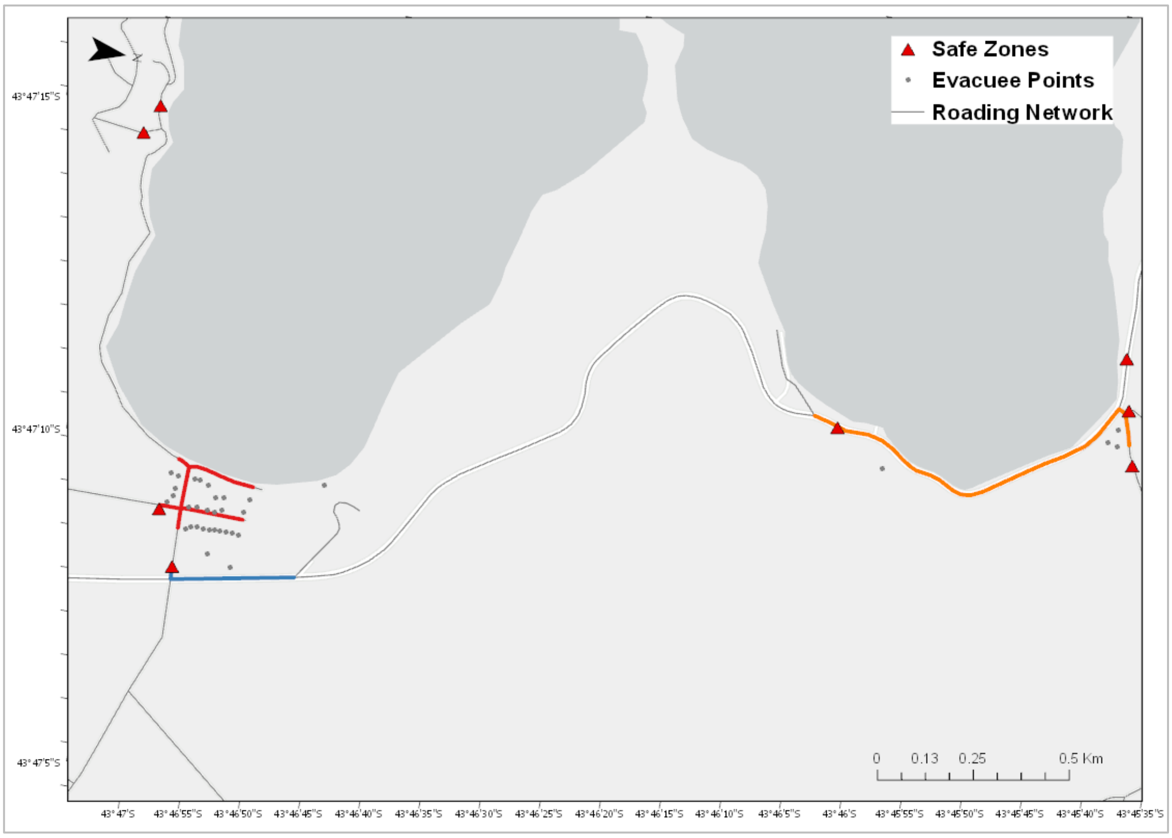

Figure 4.40: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

4.4.9 Te Oka Bay, Tumbledown Bay & Magnet Bay

Figure 4.41 shows the location and streets of Te Oka Bay, Tumbledown Bay, and Magnet Bay.

Evacuation modelling for Te Oka Bay, Tumbledown Bay, and Magnet Bay was combined. The decision to combine the modelling for these communities was based on the close proximity of these areas and the low population density. Modelling was performed for two scenarios – peak day traffic and normal traffic. In the normal traffic scenarios the time required to evacuate cars to safe zones was 0.36 minutes, increasing to 0.64 in the peak day traffic scenarios (Table 4.3).

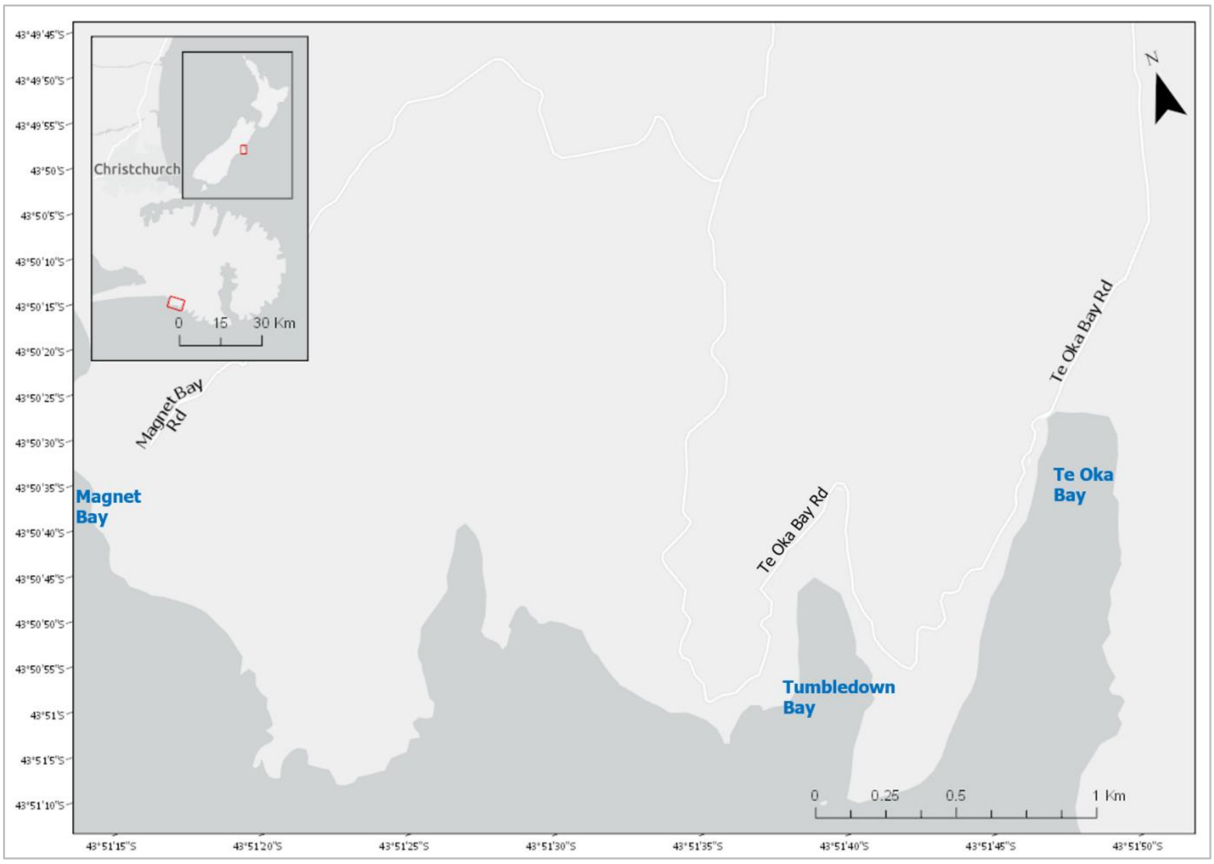

Figure 4.41: Street names of Te Oka Bay, Tumbledown Bay and Magnet Bay. Included in the map is an inset with the location Te Oka Bay, Tumbledown Bay and Magnet Bay within Banks Peninsula and New Zealand.

4.4.9.1 Vehicle Density Count

In the normal traffic scenarios there were very few vehicles evacuating the bays to the south of Banks Peninsula – one vehicle at Magnet Bay and two at Te Oka Bay. This led to low vehicle density counts during these scenarios. The vehicle density count increased during the peak day traffic scenarios. The most noticeable change was at Tumbledown Bay, where the vehicle density count increased from zero to 60 evacuating vehicles. An example of the peak day vehicle density count results is shown in Figure 4.42.

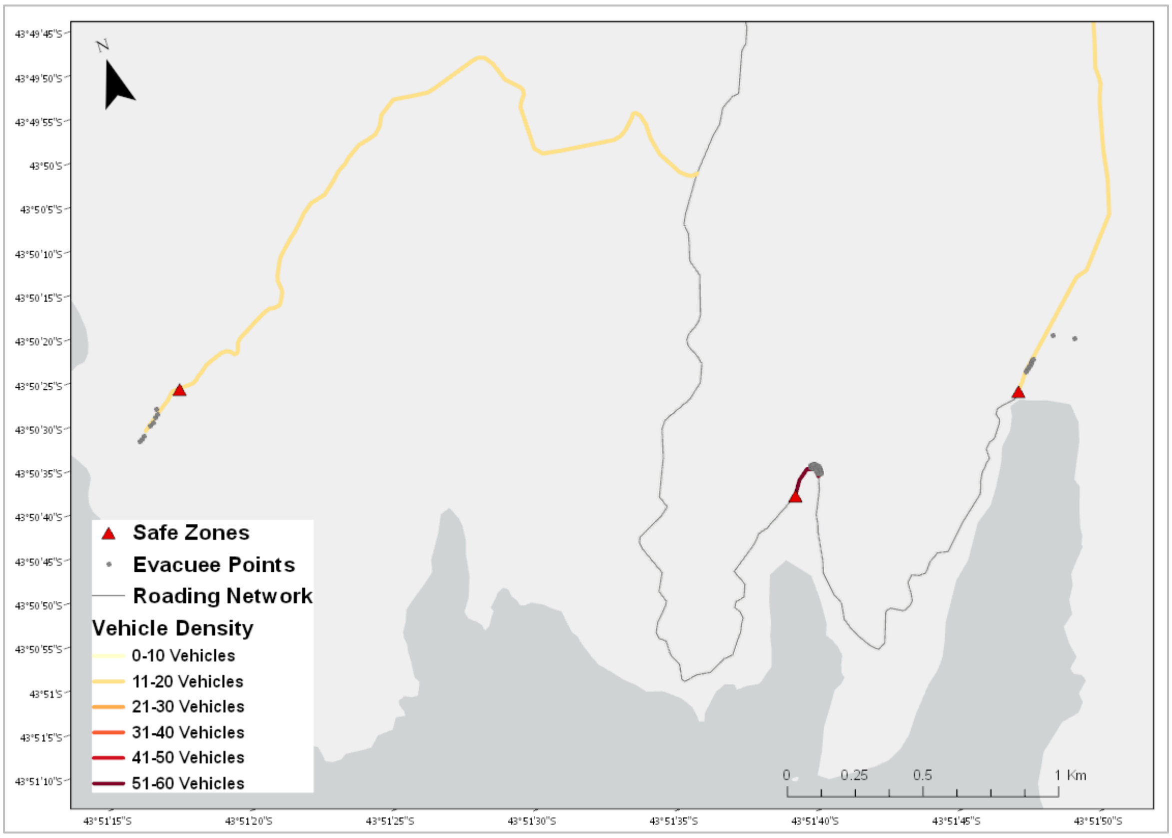

Figure 4.42: Vehicle density count results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.9.2 Evacuation Cost

Despite the observation of 60 vehicles at Tumbledown Bay during the field visit, the peak day evacuation costs ranged from 0.42-0.32 minutes when evacuating at 28.1km/hr. Magnet Bay, which had a lower number of evacuees during the peak day scenario (nine evacuees), had a higher evacuation time ranging from 0.64-0.45 minutes during the evacuation modelled at a speed of 28.1 km/hr. Similarly, Te Oka Bay, which during the same evacuation scenario was modelled with 11 evacuees for the peak day scenario and had an evacuation cost ranging between 0.58-0.17 minutes. An example of the evacuation cost results is shown in Figure 4.43.

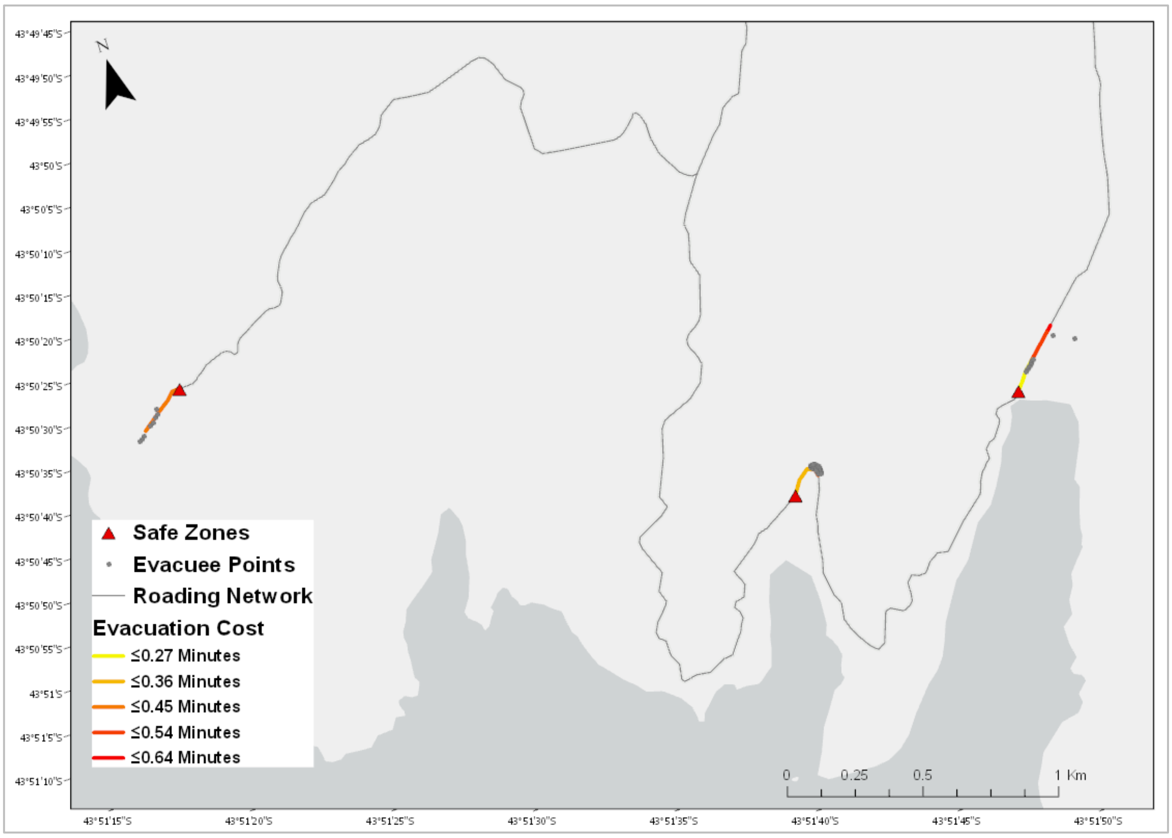

Figure 4.43: Evacuation cost results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.9.3 Safe Zone Distribution

Each bay was assigned their own safe zone. Evacuees were routed to their closest safe zone that coincided with the bay they were initially in (shown in Figure 4.44).

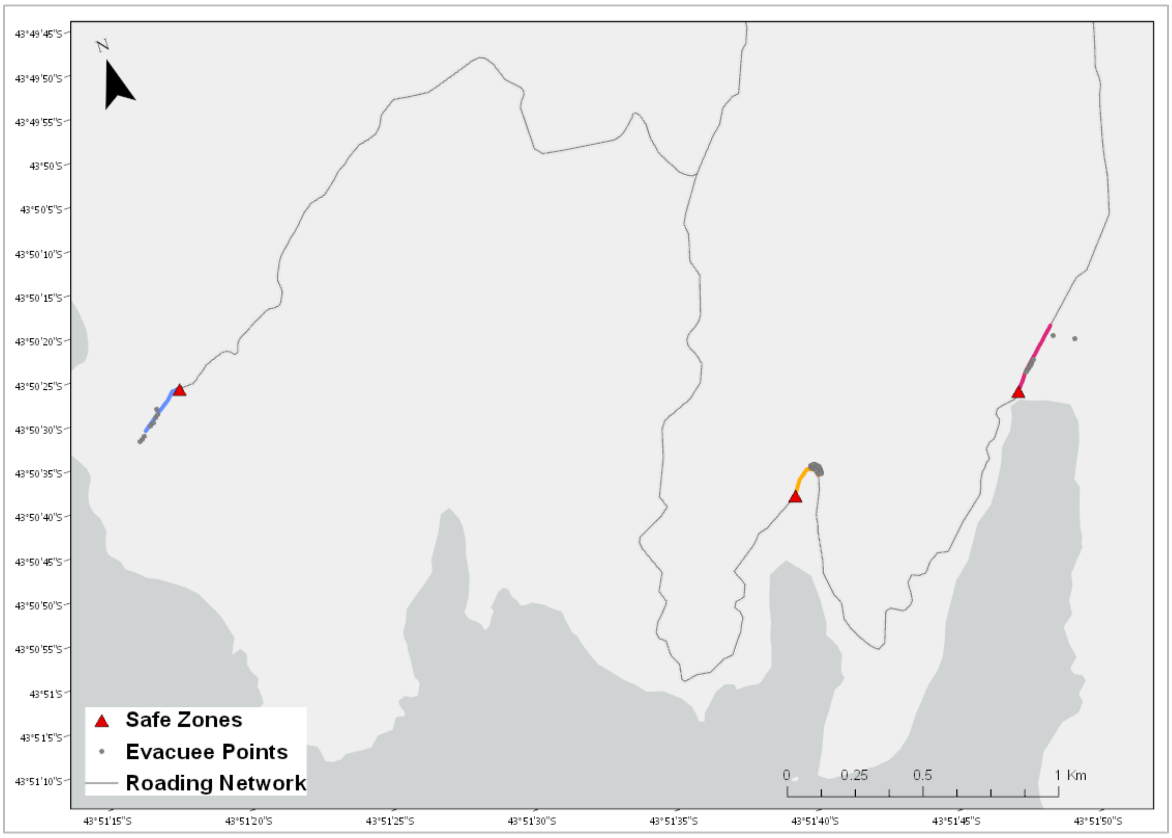

Figure 4.44: Safe zone distribution results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.10 Wainui

Figure 4.45 shows the location and streets of Takamatua Bay and Robinson Bay.

Evacuation modelling was produced for Wainui for peak day traffic and normal resident traffic scenarios. As shown in Table 4.3, the maximum evacuation time increased from 1.04 minutes during an evacuation at a speed of 50 km/hr with normal traffic, to 2.21 minutes when evacuating at 28.1 km/hr during peak day traffic.

Figure 4.45: Street names of Wainui within the tsunami evacuation zones. Included in the map is an inset with the location Wainui within Banks Peninsula and New Zealand.

4.4.10.1 Vehicle Density Count

The vehicle density count increased in the peak day traffic scenario along four road segments in Wainui. This included Cemetery Road, Wainui Valley Road, and two segments of Wainui Main Road. Based on field observations, the vehicle density count of Cemetery Road increased from 26 during the normal traffic modelling, to 72 during the peak traffic modelling. Smaller changes were evident along other roads such as Wainui Valley Road and Wainui Main Road. The vehicle density count results for a peak traffic scenario are shown in Figure 4.46.

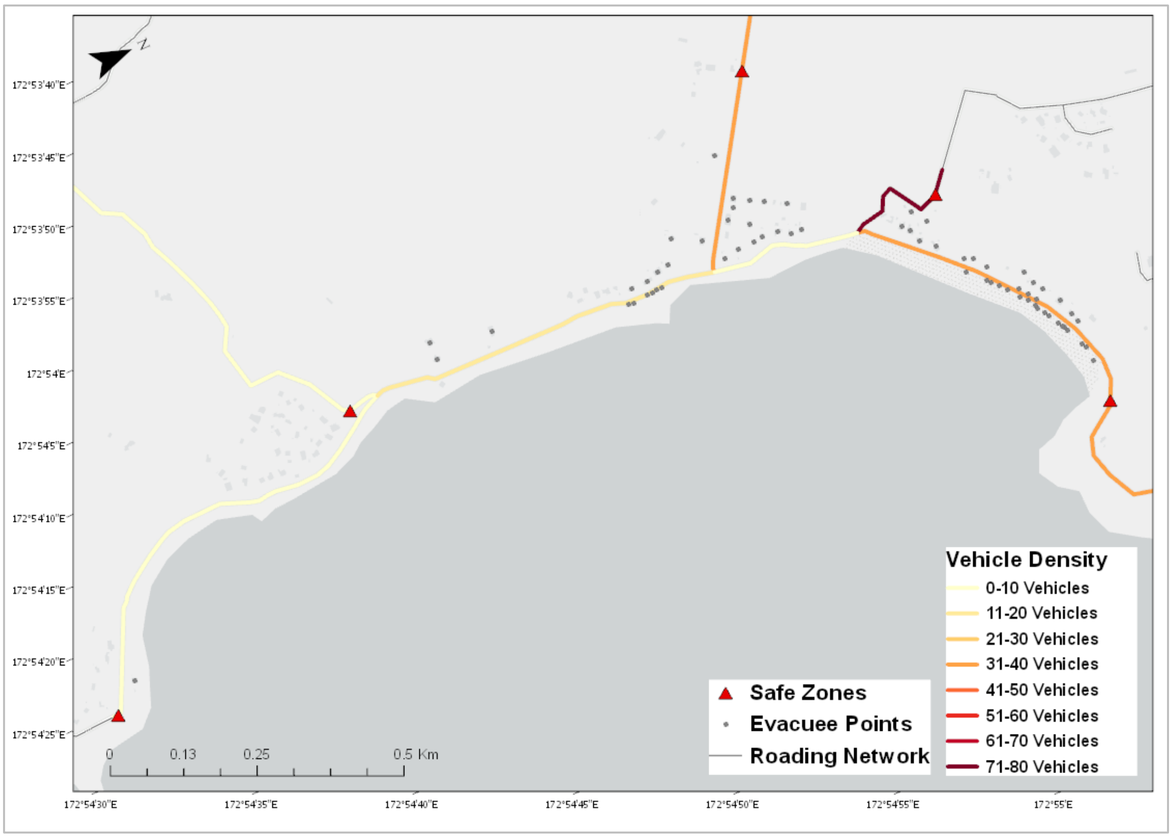

Figure 4.46: Vehicle density count results for Wainui – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

4.4.10.2 Evacuation Cost

The minimum evacuation travel time in Wainui was 0.18 minutes, observed during the normal traffic scenario at 50 km/hr, while the maximum time was 2.21 minutes during the peak day traffic scenario at 28.1 km/hr. An evacuee on Bossu Road had the shortest evacuation cost in all modelling scenarios, while longer evacuation times were associated with evacuees to the eastern side of Wainui Main Road (as shown in Figure 4.47).

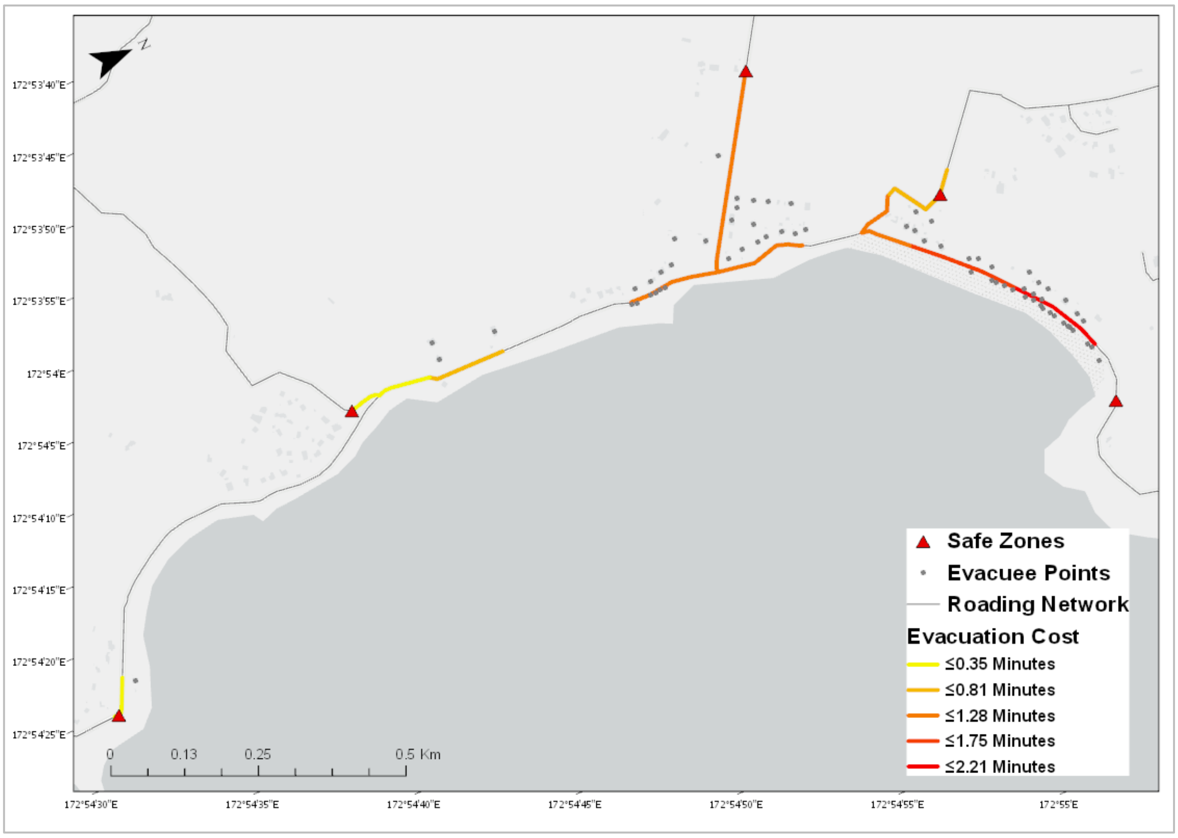

Figure 4.47: Evacuation cost results for Wainui – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

4.4.10.3 Safe Zone Distribution

The evacuation modelling tool utilised four safe zones in Wainui (as displayed in Figure 4.48). In the peak day traffic scenarios this included one evacuee being directed to Bossu Road, three to Jubilee Road, 27 to Wainui Valley Road, and 36 to Cemetery Road. Evacuees on Wainui Main Road were directed to the safe zone on Cemetery Road which was approximately 665 meters away, despite a safe zone being approximately 90 meters away (Figure 4.48). This will be discussed in Section 4.5.1.3.

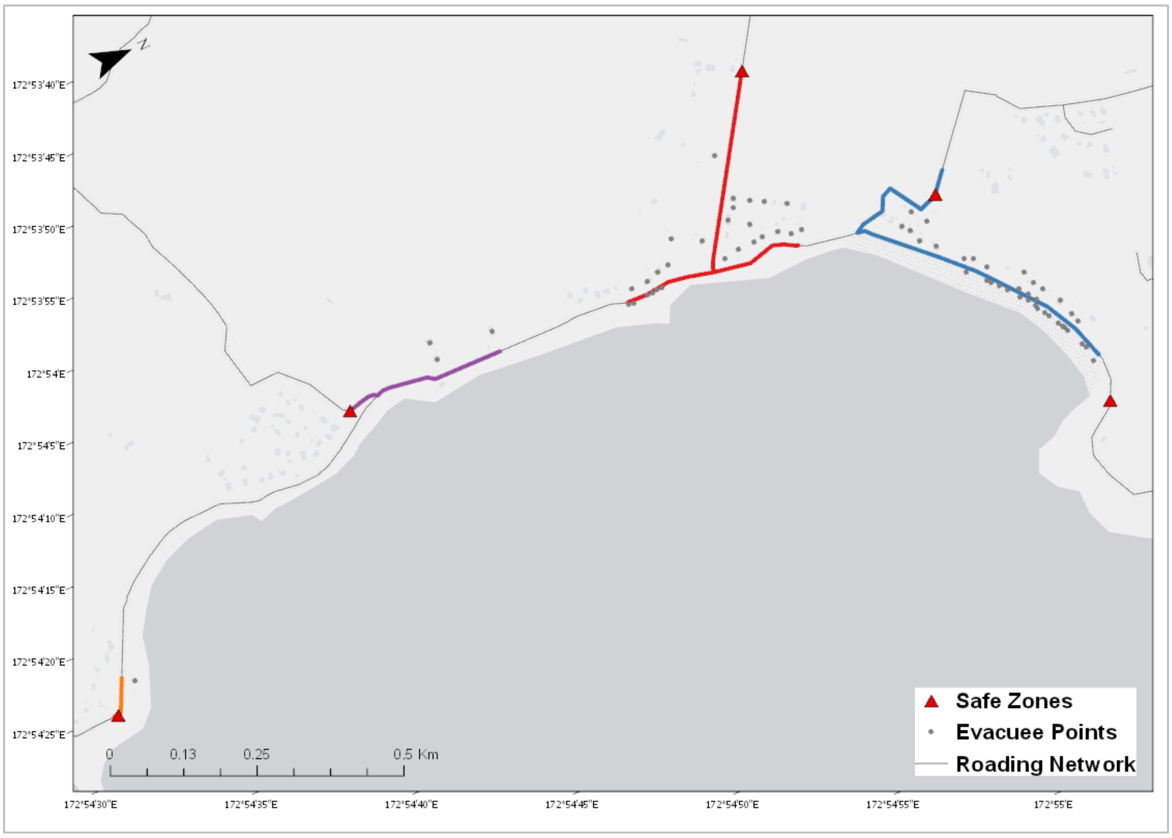

Figure 4.48: Safe zone distribution results for Wainui – modelled at an evacuation speed of 28.1km/hr during a peak day traffic scenario.

4.4.10.4 Reduction in Safe Zones

Further evacuation modelling was conducted for Wainui. In this modelling, the number of safe zones input into CASPER decreased from five to one which was located on Wainui Valley Road.

The overall evacuation cost for Wainui when using one safe zone ranged from 2.10-2.13 minutes with a speed of 50 km/hr, and 3.74-3.78 minutes when evacuating at 28.1 km/hr (Table 4.4).

Wainui Valley Road had the highest vehicle density count, ranging from 45 vehicles in the scenarios modelled for normal traffic, to 75 during the peak day traffic modelling. Wainui Main Road also had a high vehicle density count with 10 vehicles during the normal resident modelling scenario, increasing to 34 during the peak day traffic scenario. Cemetery Road had a low vehicle density count in all scenarios with two vehicles.

The highest evacuation cost was for the evacuee at the far end of Wainui Main Road. The maximum evacuation time for this evacuee was 3.78 minutes (during the peak day modelling for an evacuation speed of 28.1 km/hr). Evacuees on either side of the intersection with Wainui Main Road and Wainui Valley Road had the shortest evacuation time.

All evacuees were routed to the safe zone on Wainui Valley Road. During the peak traffic scenarios this saw 66 evacuees at this safe zone, decreasing to 37 during the normal traffic scenarios.

4.5 Discussion

4.5.1 Discussion of CASPER Evacuation Modelling Results

This section discusses the results of the evacuation modelling. Firstly, each of the three outputs are discussed, along with the results for the modeling where the number of safe zones were reduced. This is followed by a summation of what these results mean for vehicular evacuations in Banks Peninsula, and a reflection on the suitability of the CASPER network modelling extension tool. Finally, limitations of the analysis, recommendations to improve the efficiency and safety during future evacuations and areas for future work and research are presented.

4.5.1.1 Vehicle Density Count Results

Many road segments had vehicle density counts that did not change much throughout the different modelling scenarios. Examples included road segments around Robinsons Bay and Pigeon Bay. In these examples there were either few vehicles on the different road segments, or there was no substantial increase in the number of evacuees in the peak day and night modelling scenarios.

Some road segments had consistently higher vehicle density counts compared to other road segments in the different modelling scenarios. Typically this was the road segments leading to the safe zones. In some locations this was because there were no other routes that evacuees could take to reach their evacuation point. For example, in Birdlings Flat evacuees had to travel along Poranui Beach Road to reach the safe zone, resulting in this road having a high vehicle density count ranging from 157 during normal traffic, to 183 during peak day traffic (see example in Figure 4.14). In other locations, some roads appeared to be favoured by the modelling algorithm. An example can be seen in Akaroa along Rue Balguerie, which, in all modelling simulations, had the highest vehicle density count for this community (shown in Figure 4.10). This is likely to be a consequence of the spatial distribution of the evacuee origin locations which saw a high number of evacuees around this road in all modelling scenarios. Tilley (2018) used the CASPER extension to model evacuations in New Brighton, South Brighton and Southshore. Here, although a higher number of evacuees were input into the modelling tool, the roads segments that experienced the highest vehicle density counts were predominately the roads that led out of the communities towards the safe zones. These examples suggest that during an evacuation, roads leading out of the hazard zone and towards safe zones will likely experience higher traffic than other roads. This information will be useful for emergency managers in developing future evacuation plans, including the implementation of signage to encourage people to continue evacuating further to minimize congestion and ensure all evacuees can reduce their exposure.

Fraser et al. (2014) outlined that the exposure of a population within a tsunami hazard zone is typically derived from census data focusing on the distribution of night-time populations, however, acknowledged that the day time exposure can be informed by augmenting the night time population with additional information. This includes the consideration of visitors into an area (Fraser et al., 2014). For this research, this was achieved through the field observations, which provided insight into the number of evacuees that could need to relocate to safety during a tsunami event during a peak exposure scenario. The inclusion of field observations led to higher modelled vehicle densities beyond the building footprint origins alone. Examples of this are evident in Okains Bay, Birdlings Flat, Pigeon Bay, Akaroa, Duvauchelle, and Tumbledown Bay. For example, in the normal modelling scenario for Okains Bay when the origin points were informed by only the building footprints, three vehicles were routed along Okains Bay Road. However, when including field observations, the number of vehicles directed along this road segment increased to 123 during the peak day scenario, and 127 during the night scenario when including accommodation points (see Figure 4.30). In Tumbledown Bay, a cluster of 60 vehicles were observed parked on the roadside while people were spending the day at the beach. This increased the number of vehicles from zero during the normal traffic modelling scenario, to 60 during the peak day traffic (Figure 4.42). Without the inclusion of the results, the vehicle density count values for many road segments throughout Banks Peninsula would remain low, and not reflect the change in population in summer that became evident through the field observations. Therefore, including field observations when determining evacuee locations for evacuation modelling creates more realistic results and improves understanding of how a changing population number can affect evacuation traffic.

4.5.1.2 Evacuation Cost Results

Evacuation modelling literature indicates that variation in travel speed can impact the exposure of evacuating populations and their ability to relocate to safer locations, in which slower speeds lead to longer evacuation times (Wood et al., 2012; Wood et al., 2016). From this literature, it was anticipated that the maximum evacuation cost for the modelling results of this study would increase when the evacuations were modelled at a lower travel speed. In all of the evacuation scenarios the maximum evacuation cost increased in the scenarios modelled at 28.1 km/hr when compared to the scenarios modelled with an evacuation speed of 50 km/hr (shown in Table 4.3). For example, the maximum time required to evacuate vehicles in Pigeon Bay during the normal traffic scenario increased from 1.52 minutes when evacuating at 50 km/hr, to 2.71 minutes at a speed of 28.1 km/hr (see Table 4.3).

When comparing the evacuation costs for the normal resident traffic scenarios with the peak day and night traffic scenarios, six out of the ten communities where evacuation modelling was performed had an increase in evacuation cost. Increased evacuation costs occurred because there were a higher number of evacuees on various road segments, increasing the travel time for other evacuees. This was observed in areas such as Okains Bay and Little Akaloa (shown in Table 4.3). In Okains Bay, a cluster of 120 vehicles at the campground contributed to a higher overall evacuation cost, increasing from 2.71 minutes during normal traffic, to 4.66 during peak day traffic (both at an evacuation speed of 28.1 km/hr). In Little Akaloa only 12 vehicles were observed during the field observation. This contributed to a small increase in the overall evacuation time for this community. Similar trends have been observed in other evacuation modelling results, whereby increasing the number of evacuees has increase the evacuation time (Alabdouli, 2015; Shahabi & Wilson, 2018). However, in this research, despite the number of evacuees increasing in the peak day and night scenarios, the maximum evacuation cost for some areas did not increase. This occurred in Akaroa, Birdlings Flat, Takamatua Bay and Robinsons Bay, and Tumbledown Bay, Te Oka Bay, and Magnet Bay. For example, in Akaroa, the number of evacuees increased from 105 during the normal modelling scenario, to 565 during the peak day and 273 during the peak night (shown in Appendix G). While the evacuation cost for many of the evacuees in Akaroa increased slightly, the overall evacuation cost did not increase, remaining at 0.75 minutes for the scenarios modelled with a travel speed of 50 km/hr, and 1.33 minutes for those with a travel speed of 28.1 km/hr (Table 4.3). This was an unexpected result of the modelling scenarios, as it was anticipated that increasing the number of evacuees would increase the overall evacuation time for a community (Alabdouli, 2015; Shahabi & Wilson, 2018).

Safe zone locations where evacuees were directed to by the modelling algorithm were influential in the evacuation cost for individual evacuees. In many cases, evacuee origin points were very close to the safe zone points. For example, an evacuee in Wainui was 66 meters from a safe zone (Section 4.4.10), while in Magnet Bay an evacuee had to travel 117 meters (see Section 4.4.9). A cluster of 60 vehicles observed at Tumbledown Bay, shown in Section 4.4.9, all evacuated approximately 280 meters to their evacuation safe zone. In these examples, evacuees had low evacuation costs influenced by short travel distances. In other locations evacuees were routed larger distances, with higher evacuation costs, such as in Duvauchelle and Robinsons Bay. In Duvauchelle, an evacuee was directed along an evacuation route of approximately 880 meters to reach a safe zone (from Duvauchelle School Lane to the intersection of Pipers Valley Road and State Highway 75), resulting in a travel time ranging 1.05-2.19 minutes in all modelling scenarios (see Section 4.4.4.2). While there was some congestion at the end of this route, the long distance likely contributed most to the high evacuation cost. Similarly, three evacuees in Robinsons Bay were directed 960 meters from their origin points to safe zones, and had a travel time of up to 2.06 minutes during the peak day scenario when evacuating at 28.1 km/hr (see Section 4.4.8.2). This was despite only a small number of additional evacuees from the vehicles counted during the field observations.

As stated in Section 4.3, the modelling results did not account for participation in any pre-evacuation actions or behaviours that may delay residents' evacuations. These data was recorded in the evacuation behaviour survey (Section 3.4.2), and as highlighted by MCDEM (2018c), can be used following the completion of the modelling. Applying these data to the maximum evacuation time produced by the CASPER modelling algorithm is useful as it produces a more holistic evacuation time that includes the time to respond and react to the warning, prepare to evacuate and the evacuation journey itself (Fraser et al., 2014; Makinoshima et al., 2020; Trindade et al., 2018). The results that are produced are more comprehensive and representative of the full evacuation process (Makinoshima et al., 2020). Including these data allowed for the inclusion of actions residents may partake in prior to evacuating (with residents from Banks Peninsula reporting partaking in actions including gathering household and family members, pets and life essentials, or discussing the evacuation plan during the 2016 evacuation, as shown in Figure 3.9), along with the time required for transient visitors to return to their vehicles and begin their evacuation journey. The complete survey dataset (Christchurch and Banks Peninsula) reported that 37% (n=60) of evacuees took between 1-10 minutes to get ready to evacuate, and 31% (n=50) took between 10-30 minutes to get ready (Section 3.3.2.1). In Banks Peninsula, times for pre-evacuation behaviours and actions were provided for Akaroa (n=1), Birdlings Flat (n=11), and Little Akaloa (n=1). Similarly to the overall data set, the most common times taken were 1-10 minutes (31%, n=4), and 10-30 minutes (38%, n=5). When incorporating these self-reported data with the modelled results, the time required to evacuate these communities' increased to between 1.26-34.69 minutes for the modelling results produced utilising all possible safe zones. The increase in evacuation time when incorporating these data provides a better understanding of the time required to evacuate these areas and can be used to compare against the tsunami wave arrival time (Fraser et al., 2014).

4.5.1.3 Safe Zone Distribution Results

In many areas, a limited number of safe zones were input into the CASPER modelling tool for evacuees to be directed to. For example, evacuees in Birdlings Flat, Te Oka Bay, Magnet Bay, and Tumbledown Bay were routed by the CASPER algorithm to the only possible safe zone. In other examples multiple safe zones were input into the CASPER tool for evacuees to be directed to, as seen in the modelling results for Akaroa, Okains Bay, Little Akaloa, and Pigeon Bay. Evacuee points input into the CASPER modelling algorithm were directed to evacuate to their nearest safe zone point. The spatial distribution of the population meant that some safe zones had a higher number of evacuees directed to them compared to others, for example, along Big Hill Road in Okains Bay (see Figure 4.32) or Rue Balguerie in Akaroa (shown in Figure 4.12). These results can be used to identify hot spots, and central evacuation routes and safe zones that could help guide the location of potential evacuation locations and welfare centres.

The CASPER modelling tool sorts evacuees by distance and directs them to the closest safe zone (Shahabi, 2012). In some of the modelling scenarios for this research this did not occur, and instead evacuees were directed to safe zones that were further away. In Wainui, Robinsons Bay, Akaroa, Pigeon Bay and Okains Bay, evacuees were routed to distant safe zones despite the presence of closer ones. For example, in Wainui, an evacuee on Wainui Main Road was directed to a safe zone along Cemetery Road, despite being close to a safe zone on Wainui Main Road (Figure 4.48). In the peak night traffic evacuation model for Pigeon Bay, evacuees on Holmes Bay Road were directed to a safe zone further along the road they originated on, despite being closer to a safe zone on Pigeon Bay Road (shown in Figure 4.36). These results were unexpected, as it was anticipated that the modelling algorithm would have instead routed these evacuees to their closest safe zone (Shahabi, 2012).

Thorough investigation of the modelling tool did not yield answers as to why evacuees were not directed towards their closest safe zone. Makinoshima et al. (2016) identified that modelling results often reflect behaviours of an ideal evacuee and are not always representative of an evacuating population who, for example, may not evacuate to their closest safe zone. The results of this research are not always reflective of ideal evacuee behaviour, with evacuees being directed to indirect safe zones and unintentionally reflect evacuation routes and actions that people may take during an evacuation if they do not know the location of tsunami evacuation zones or their closest safe area. Therefore these results are beneficial in providing a more holistic understanding of evacuation dynamics, incorporating a range of behaviours, not just limited to evacuating to the closest safe zone.

4.5.1.4 Reduction in Safe Zones

Additional evacuation modelling was simulated for four areas of Banks Peninsula, in which the number of safe zones were decreased. The results from this modelling (Table 4.4) showed that the maximum evacuation cost increased when compared to the initial modelling. The smallest evacuation time was for an evacuation in Akaroa at a speed of 50 km/hr with normal resident traffic, where the evacuation cost was 0.80 minutes. The largest evacuation cost was observed in Okains Bay, where it was estimated by the modeling tool that it would take a maximum of 8.88 minutes during night traffic when evacuating 28.1 km/hr to relocate to safe zones. As outlined in Section 4.5.1.2, evacuation delay data can be incorporated into the total evacuation cost following the completion of the modelling (MCDEM, 2018c). When incorporating the evacuation delay that was most commonly recorded in the survey (1-30 minutes), the evacuation cost for these scenarios increased to between 1.80-38.88 minutes. Incorporating these data produces more realistic results that incorporate the entire evacuation process including reactions to warnings, decision making and the evacuation journey. These results are more comprehensive when compared to only considering the time of the evacuation journey as they provide a more holistic overview of the evacuation that will be more informative for improving tsunami risk management strategies (Makinoshima et al., 2020).

In the modelling scenarios where the number of safe zones were decreased, evacuees were directed towards the same safe zones. This implication of this was that the vehicle density count values increased primarily on road segments where the safe zones were located, but also along some of the roads leading to the safe zones. Although evacuees close to safe zones had lower evacuation costs compared to other evacuees (for example Lukes Road in Little Akaloa and Bruce Terrace in Akaroa), overall individual evacuation costs increased for other evacuees. These results highlight that when there are fewer locations for evacuees to relocate to during a tsunami evacuation, there are more congestions and bottlenecks that lead to longer evacuation travel times. These results are consistent with research conducted by Harris et al. (2015) where evacuation modelling was performed for a hazardous material incident. In their research, evacuation modelling was conducted initially, and then altered where an evacuation route was blocked by a train (Harris et al., 2015). This increased the total time required for people to relocate to safety (Harris et al., 2015) and is a similar concept to the reduction of safe zones in this research.

4.5.1.5 Summary of Evacuation Modelling Results

The evacuation modelling results highlighted some trends and factors that would increase the exposure of evacuees during an evacuation. In the initial modelling, the total evacuation cost increased for six out of the ten communities when the number of evacuees increased (Table 4.3). The evacuation costs for individual evacuees also increased in all areas when there were more vehicles evacuating in the peak day and night scenarios. While distance played a role in the evacuation travel time, it was congestion that mainly increased evacuation costs. Despite variation in the vehicle density count throughout the communities, as the number of evacuees increased the vehicle density count also increased. This was observed along road segments where evacuees were observed during the field visits, along with road segments leading to safe zones. These factors suggest that in some areas there could be congestion and bottlenecks during a tsunami evacuation, potentially leaving people exposed in coastal zones.

In four areas the number of safe zones were reduced, allowing for further incorporation of empirical data, while also replicating what may happen if evacuees were not aware of all of the places they could evacuate to or if the accessibility of roads was decreased due other hazards like rockfall. In these evacuation scenarios there was more pressure on the road network capacity to handle the increase in vehicles going to a limited number of safe zones. The results of this modelling showed that while some roads experienced a decrease in vehicle density, most roads leading to the safe zones, experienced an increase in vehicle density count values. This increase was more pronounced in areas where there were more vehicles. The increase was also evident when the number of evacuees increased in the peak day and peak night traffic scenarios. The removal of safe zones resulted in more vehicles travelling to and from the same areas, which increased the maximum evacuation costs, both for individual evacuee costs and for the overall community. Similar to the initial modelling, the results indicated the likelihood of congestion and bottlenecks, particularly where there was a higher concentration of vehicles and on roads leading to the safe zones.

In the evacuation modelling where all safe zones were utilized, the maximum evacuation cost was less than five minutes (Table 4.3). These results indicate that in perfect conditions if people immediately respond to a natural or official tsunami warning and know where to evacuate to, there is time for exposed populations in Banks Peninsula to relocate to safer ground for a regional or distant source tsunami threat (Jack & Schoenfeld, 2017). There would potentially be time to evacuate and reduce exposure during a local source tsunami threat, however, this is dependent on the location of the tsunami source and the travel time to reach Banks Peninsula communities. The evacuation times shown in Table 4.3 are similar to the time required for residents of Sumner (Christchurch, New Zealand) to evacuate by vehicle and reduce their tsunami exposure (Le, 2016). If all vehicles in Sumner evacuated at the same time, they would all exit the hazard zone after two minutes (Le, 2016). The evacuation times shown in Table 4.3, along with the estimated evacuation time for Sumner (Le, 2016) are much smaller than the evacuation times estimated for residents of Southshore, South Brighton, and New Brighton (Christchurch, New Zealand) to evacuate by car, where it was modelled that the maximum evacuation time was 280 minutes (Tilley, 2018). While the studies produced by Le (2016) and Tilley (2018) both had a higher number of origin points compared to the number of evacuees input into the scenarios for this Masters research, a comparison of the maximum evacuation time suggests that topographical factors such as accessibility to higher ground is extremely influential in the evacuation cost.

As stated above, the evacuation times were noted to increase when there were more evacuees. The maximum evacuation cost also increased when the evacuation conditions were imperfect. For example, in reducing the number of safe zones, the maximum evacuation cost increased to 8.88 minutes (Table 4.4). Further increases in the maximum evacuation cost occurred when incorporating empirical data representing the time required for evacuees to respond and react to the tsunami warnings and begin their evacuation journey during the 2016 Kaikōura earthquake tsunami. Combining these data with the evacuation cost caused the maximum evacuation cost to increase to a maximum of 38.88 minutes. While there would be time to evacuate these populations for a distant source tsunami, there becomes less clearance time to evacuate to safety against a regional source tsunami which has a travel time of 1-3 hours. In these imperfect evacuation conditions there may be insufficient time to evacuate (following a delayed response and reaction) during a local source tsunami threat. There is a low risk of a damaging local source tsunami in Banks Peninsula, with there being no known local tsunami sources off the coast of Banks Peninsula (Jack & Schoenfeld, 2017). However, the results explained above become concerning when considering that an offshore earthquake fault or underwater landslide in Pegasus Bay or Canterbury Bight could generate a local source tsunami that could flood land in Banks Peninsula (Jack & Schoenfeld, 2017). This is because of how the tsunami waves are funneled and amplified when entering the narrow harbours and bays of Banks Peninsula (Jack & Schoenfeld, 2017). This risk increases if people in these coastal areas are unaware of how to interpret the natural warnings and do not respond by immediately evacuating. This demonstrates the importance of effective tsunami risk management through education and evacuation planning to ensure efficient and prompt evacuations. Recommendations to ensure this will be discussed below in Section 4.5.4.

4.5.2 Suitability of CASPER as an Evacuation Tool

This section reflects on the suitability of the ArcCASPER network analyst evacuation modelling tool. The tool was easy and straightforward to use, and was user-friendly in enabling input changes such as safe zones and the origin points which allowed for different modelling scenarios to be simulated quickly. Different attributes were assigned easily to the network, allowing for different costs/speeds to be incorporated and changed; for example, between the 50 km/hr and 28.1 km/hr evacuation speeds. The CASPER algorithm computed the outputs in minutes.

The CASPER tool has only been used a limited number of times in published research (including Alabdouli, 2015; Harris et al., 2015; Knook et al., 2015; Shahabi & Wilson, 2014l Shahabi & Wilson, 2018; Trindade et al., 2018). There are few resources that include specific details on how to use the tool, while there is also a lack of support for the tool itself. This made it difficult when it came to problem solving issues within the tool or the outputs. When solving the evacuation routing problems some road segments were excluded from the analysis domain, thereby excluding associated evacuee origin points (shown in Figure 4.49) and safe zone destination points. Figure 4.50 provides an example of where a safe zone in Wainui was excluded. Some road segments also were not utilised by the modelling tool and evacuees were directed along indirect routes to reach safe zones, as shown for Okains Bay in Figure 4.51 (further examples can be seen in Figure 4.12, Figure 4.40 and Figure 4.50). While attempts were made to complete modeling with a reduced number of safe zones, this could not be completed as a large number of evacuees were excluded from the modelling analysis domain resulting in incomplete modelling. Despite ensuring that road segment polylines were connected topologically, this did not resolve the issue. While the issue of excluded origin points was resolved by relocating them to the road network edges within the analysis domain (Figure 4.52), the limited publications and support for the ArcCASPER tool meant that problems of safe zones and road segment selection could not be addressed within the scope of this research. Similar issues were noted by Tilley (2018) who reported that the outputs produced by the CASPER modelling tool highlighted road segments that were excluded during the modelling process and also did not connect a cluster of evacuees to a road segment subsequently excluding them from the analysis. Further examples of where evacuee origin points had to be relocated can be viewed in Appendix H.

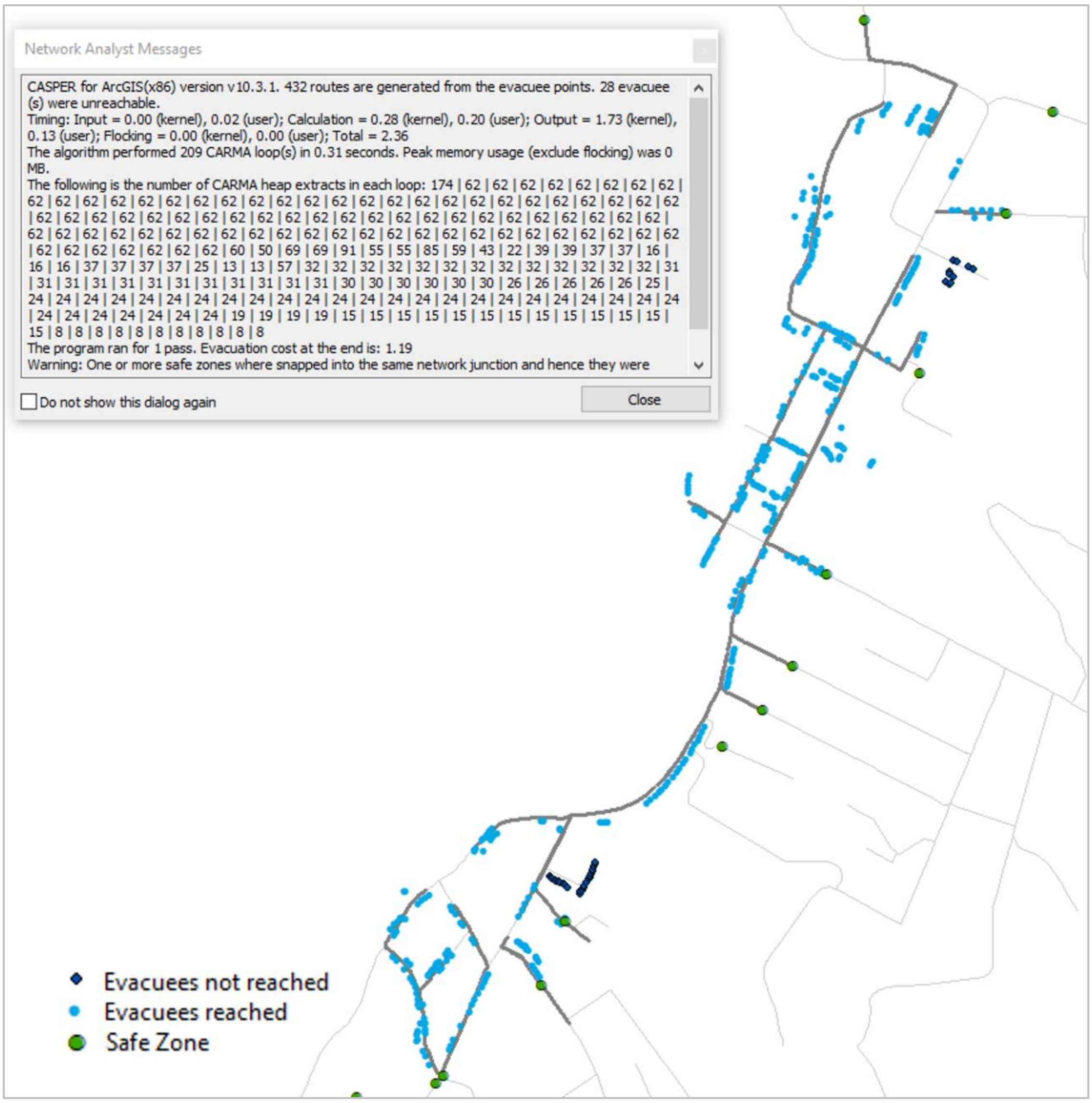

Figure 4.49: Example of CASPER evacuation routing problem. In this example, 28 evacuees were excluded from the analysis domain (shown in dialogue box). The dark blue dots represent excluded evacuees, and light blue dots are evacuees that were included.

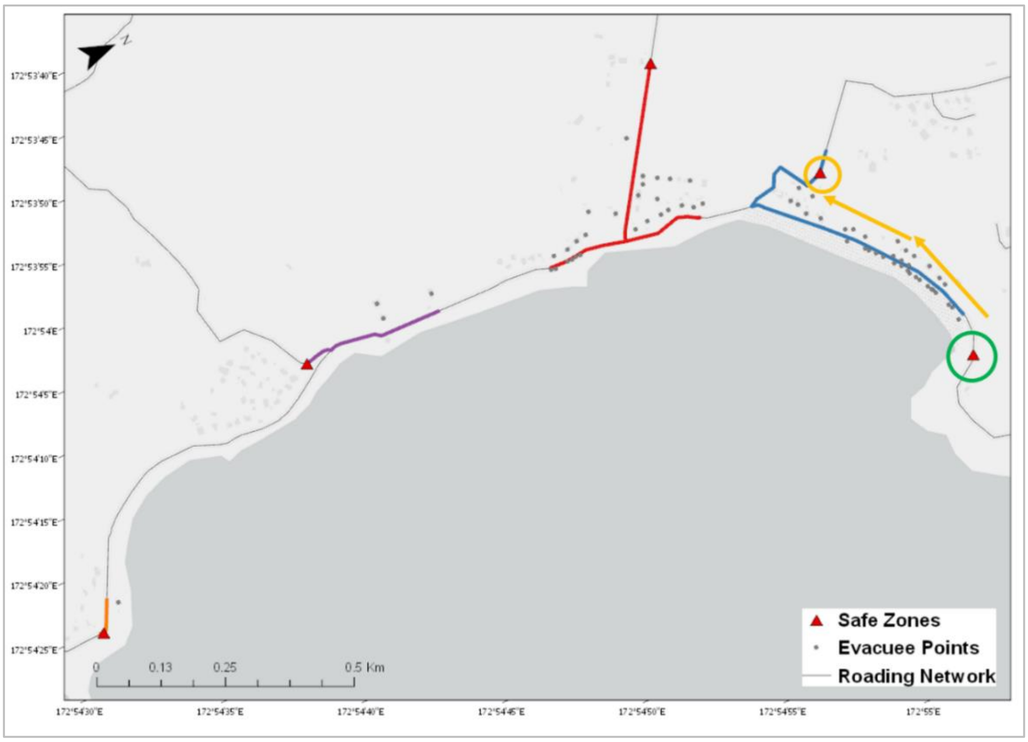

Figure 4.50: Safe zone distribution results for Wainui – modelled at an evacuation speed of 50km/hr during a peak day traffic scenario. The figure has been annotated to show the safe zone on Wainui Main Road in the green circle that had no evacuees directed towards it. Evacuees close to this safe zone were instead directed to the safe zone on Cemetery Road (in orange circle).

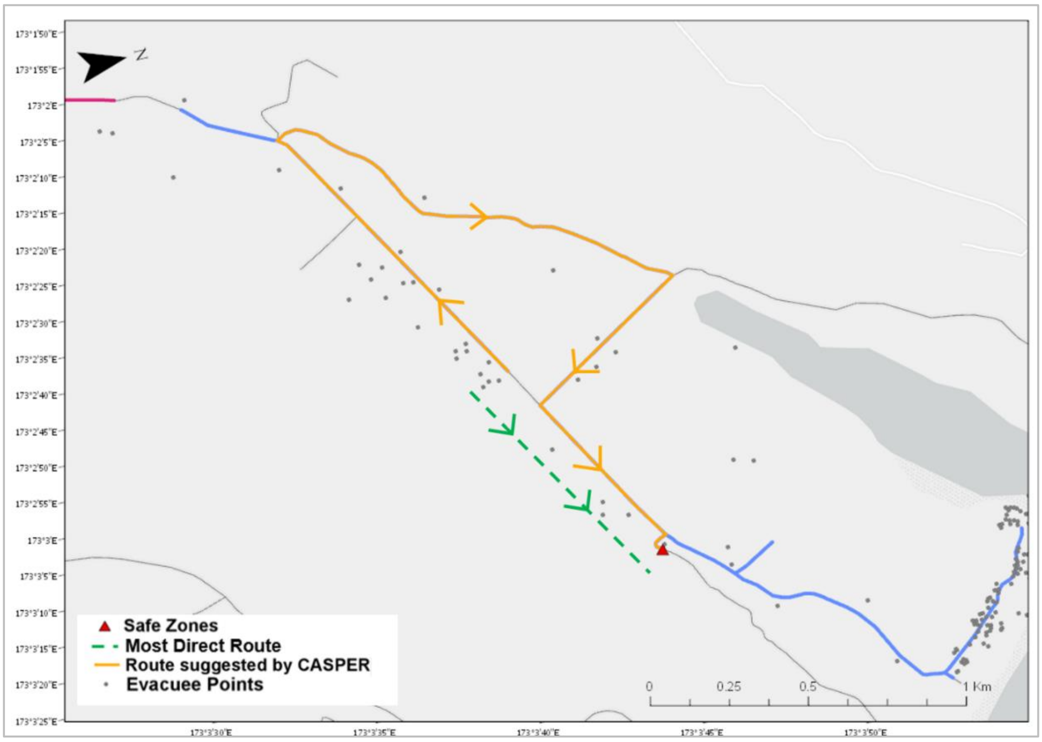

Figure 4.51: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 50km/hr during a normal traffic scenario with only two safe zones. The figure has been annotated to include arrows showing the evacuation route of evacuees. Rather than following the green route to the safe zone, the evacuees have been directed along a longer route shown by the orange route.

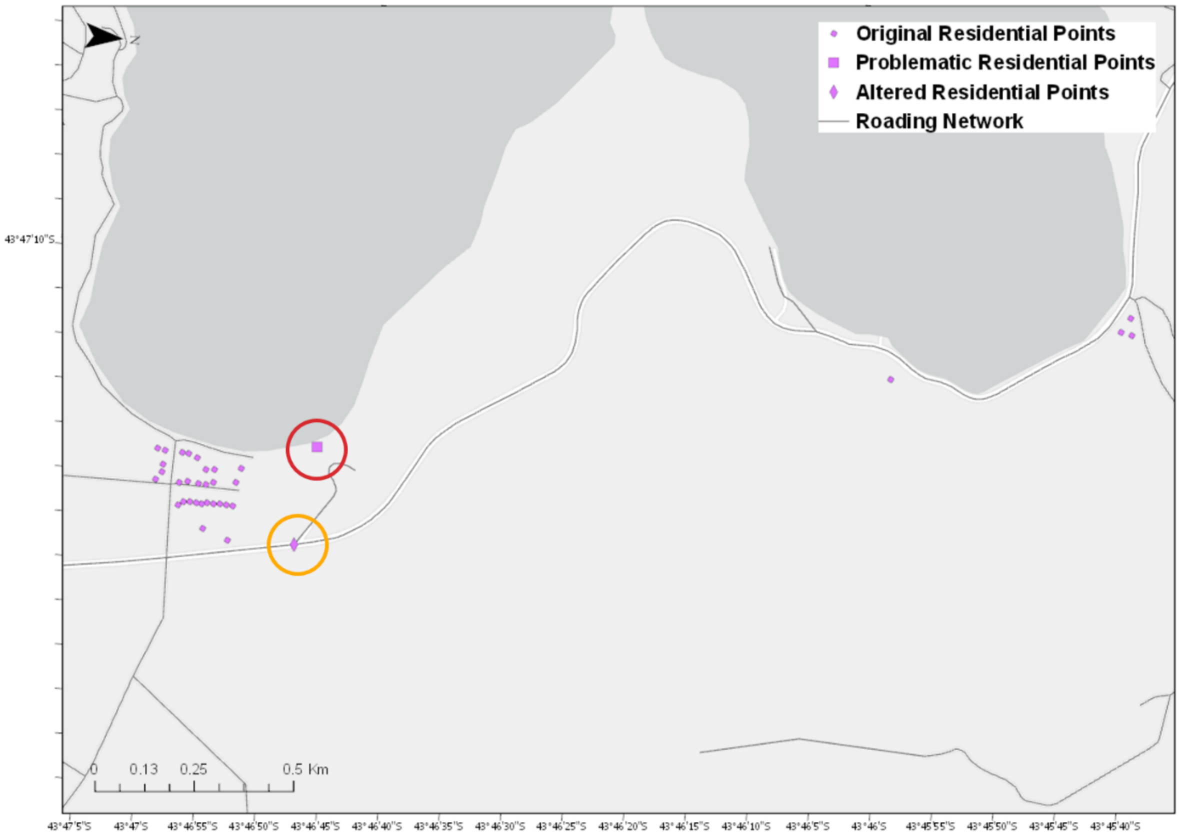

Figure 4.52: Original locations of input residential points for Takamatua Bay and Robinsons Bay. Squares represent points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circle). The diamond represents where the point was moved to ensure the model worked successfully (in the orange circle).

The flocking feature influenced the decision to use CASPER for this Masters research. This feature produces an output that shows changing evacuee locations as single points at each evacuation step. While multiple attempts were made to produce this output, it did not work and resulted in ArcMap freezing and restarting. This was despite seemingly small study areas and input numbers. This suggests that a more powerful computer is required to produce this output.

One of the outputs generated from the CASPER tool was the total evacuation cost, representing the maximum time for all evacuees to relocate to safe zones and reduce their tsunami risk. Some of these results did not always change to reflect the different modelling scenarios. For example, as shown in Table 4.3 the evacuation cost in Akaroa remained at 0.75 minutes in all three scenarios when evacuating at a speed of 50 km/hr, despite the addition of 460 evacuees during the day and 168 during the night modelling scenario. Similar results were evident in Takamatua Bay and Robinsons Bay, where the evacuation cost did not change between different traffic scenarios. These low evacuation costs may be realistic, and caused by local geographic characteristics by which evacuees are relatively close to safe zones. The CASPER modelling tool has been used successfully in previous research (including Alabdouli, 2015; Harris et al., 2015; Shahabi & Wilson, 2014; Shahabi & Wilson, 2018; Tilley, 2018;

Trindade et al., 2017). However, in these examples the populations and areas were much larger than assessed in this research. For example Shahabi & Wilson (2014) considered multiple evacuation scenarios ranging from 17,500 vehicles over 132 points to 130,000 vehicles over 859 points; Shahabi & Wilson (2018) considered 13 evacuation scenarios with a range of 24,724-423,824 vehicles; evacuation modelling for areas of Christchurch, New Zealand by Tilley (2018) involved 4,415 points representing evacuating vehicles. Therefore, it may be that this tool is better suited to large datasets. To improve understanding of whether these results are accurate, it would be beneficial to validate these results. This could be achieved through comparing the evacuation routes and costs produced by ArcCASPER to the evacuation behaviour survey data. The survey results include evacuation routes and estimated duration for respondents from Okains Bay, Akaroa, and Little Akaloa, and information on safe zones and origin points (which were used to inform the modelling). The evacuation journey times reported by the survey respondents are all 5 minutes (Section 3.3.2.4), compared to shorter modelled times in all areas for the normal resident population traffic modeling scenario (Table 4.3, Table 4.4). The difference in the evacuation cost between the survey results and the modelled results may be because in the empirical data evacuees travelled beyond the edge of the evacuation zones, therefore travelling further than the safe zones that were input into the model. An additional validation method would be driving from the evacuee origin points to the safe zones at the speed used in the modelling, and timing the duration of this journey. Although this would not consider evacuation congestion, it would indicate individual travel times, which could be used to assess accuracy of overall evacuation cost. Validation of the modeling results could also be achieved by modelling the specific evacuation routes that were reported in the evacuation behaviour survey (origin to destination point), both with and without additional traffic.

The CASPER outputs provided insight into where congestion or bottlenecks may occur, and indicated likely evacuation routes and safe zones. This information can be used to identify the locations of evacuation safe zones that could be pre-established prior to an event. The CASPER tool, however, was limited in its integration of modelling inputs with survey empirical data. While congestion speed was easily input into the model through the road network attributes, it was much harder to incorporate other survey data. One of these was the delay in evacuation. The way these data were incorporated, by considering the overall evacuation cost in regards to the evacuation delay, assumed that everyone evacuated at the same time. This is not reflective of a real-world evacuation. The evacuation behaviour survey data showed variation in when people evacuated, with some evacuating immediately and others taking various amounts of time (Section 3.3.2.1). Field observations showed that people would park their vehicles and walk towards the coast. For example, in Tumbledown Bay people parked and walked down to the water, while in Akaroa people parked throughout the township and walked towards the shops and waterfront. In an evacuation, people would therefore need to walk/run back to their vehicles, with variation in people beginning their evacuation journey relating to how long they took to reach their vehicle. Incorporating evacuation behaviour such as this may be more achievable using other modelling approaches such as Agent-Based Modelling (Table 2.3) and will be further discussed in Section 4.5.5.3.

4.5.3 Limitations

4.5.3.1 Safe Zone Destinations

The modelling only addressed people reducing their exposure by evacuating to safe zones and did not consider where evacuees went after this. In the evacuation behaviour survey, evacuees in Birdlings Flat reported that during their evacuation they went past the safe zone that was input into the model on State Highway 75, with some evacuees travelling towards Christchurch and others travelling towards Akaroa (see Figure 3.23 and Figure 3.24 in Section 3.3.2.4). Similar trends were reported from other evacuees who travelled past the input safe zone, but travelled further towards other locations. This is a limitation of this research as the model considers only evacuees evacuating from the community to the spatially designated safe areas, but does not consider where they may go subsequently. As it is likely that people will travel further than the modelled safe zones, this is likely to have implications on the road density of other roads, and the evacuee cost – both for individuals and overall.

4.5.3.2 Speed Limit of Road Network

As the speed delineation along roads was not known, a 50 km/hr average road speed was chosen (Section 4.3.1.1). This assumption was made due to the knowledge of speed limits in many New Zealand townships being 50 km/hr and the topography of the land in Banks Peninsula in there being windy narrow roads that limit the ability to drive at excessive speeds. It is acknowledged that the speed limit in towns where modelling has been completed will be above and below the assumed limit of 50km/hr, such as along sections of Beach Road in Akaroa or along the open roads on the outsides of the townships. Therefore the evacuation cost that has been assigned to evacuees may be slightly lower or higher than they would be in a real evacuation. Further to this, it is recognized that evacuees may not travel the road speed limits during an evacuation. While survey respondents reported that they travelled the normal road speed, observations were made in Sumner and New Brighton during the 2016 Kaikōura earthquake tsunami evacuation that "*most people travelled over the speed limit".* This would have further implications on the evacuation cost produced by the evacuation modelling that could result in the evacuation cost for some evacuees being lower than the results that have been produced.

4.5.3.3 Origin Points

As discussed in Section 4.5.2, issues within the evacuation modelling tool meant that for some evacuee points to be included, they had to be relocated. This included moving origin points to be directly on the road network (for example, in Akaroa and Okains Bay), or merging multiple points into one (for example, in Birdlings Flat). This meant evacuees travelled less distance than they would have if they were evacuating from their original points. Subsequently, individual evacuation costs may be lower than they would otherwise be, with similar implications on the overall evacuation time for the areas where there issues occurred.

4.5.3.4 Residential Houses

While it was known that many of the houses throughout Banks Peninsula are holiday houses or baches, the exact locations of these was unknown (Section 4.3.1.2.1). Therefore, a conservative approach was taken to assume that all houses were residential, with full-time occupancy. The normal traffic modelling scenarios have therefore likely been over-estimated evacuee numbers and attendant road vehicle densities. Evacuation costs are subsequently likely to be higher in the normal resident modelling scenarios than they would be in reality.

4.5.3.5 Use of Survey Data

The incorporation of survey data in modelling produces results that are more accurate and reflective of communities (Kubisch et al., 2019). This research provided the opportunity to use empirical data focusing on the full evacuation process that was recorded following the 2016 Kaikōura tsunami evacuation to inform evacuation modelling. The focus was on the modelling for Banks Peninsula, as tsunami evacuation modelling had not been previously produced for this area. The survey return rate for Banks Peninsula was 7.5% (Table 3.4), and only 50% (n=13) of these respondents actually evacuated during this event (shown in Figure 3.11 and Figure 3.13). This gave few responses to inform the evacuation modelling. Therefore, the decision was made to use survey data reported by both Banks Peninsula and Christchurch respondents (4.3.1). While this gave useful results that will be beneficial for emergency managers, it is acknowledged that there are differences between these two areas that would likely influence the survey results. For example, communities in Christchurch are denser and more built-up compared to the isolated communities in Bank Peninsula, so would likely have a higher number of evacuees, contributing to more congestion. There are also topographical differences, with some areas of Christchurch (e.g. New Brighton, North New Brighton, Southshore, and South Brighton) being on flat land meaning larger distances need to be travelled inland to reach safe zones, compared to most of the Banks Peninsula areas where the communities are surrounded by steep slopes, making for quick evacuations to higher ground.

4.5.4 Recommendations

The ArcCASPER evacuation modelling suggests that under different day and night time, and travel speed scenarios, when those in exposed Banks Peninsula coastal zones evacuate immediately following an official warning or long or strong earthquake shaking, and are aware of the safe zones they could evacuate to, there would likely be enough time to evacuate by car to reduce exposure from a tsunami threat. When the number of safe zones is reduced, leading to increased pressure on the road network, evacuation costs increase but travel times are still less than 10 minutes. This suggests that in these coastal rural communities, even when there is an increase in the number of evacuees due to transient visitors, or the number of safe zones has decreased and there are more vehicles heading to the same locations, bottlenecks and congestion have minor implications for evacuation times.

However, when incorporating the evacuation delay data reported in the evacuation behaviour survey (Section 3.3.2.1), the time required for these communities to evacuate increases to a maximum of 38.88 minutes. Therefore, it is crucial that people know how to react and behave upon receiving a natural or official tsunami warning and know where to evacuate to. If this does not happen during an evacuation in Banks Peninsula, there is likely to be congestion and bottlenecks as drivers follow other vehicles to the same safe zones, with people increasing their exposure by spending more time in the coastal areas. This highlights the importance of the continuation of evacuation planning and tsunami education within these communities. This will ensure that in future evacuations people know how to interpret tsunami warnings and where to evacuate to, ensuring that they can reduce their exposure by efficiently evacuating to safer ground or further inland. Below are examples of education and evacuation planning that could be implemented in Banks Peninsula to ensure efficient tsunami evacuations.

4.5.4.1 Education

Education is a crucial step in tsunami risk management and assists the public in understanding their risk, and providing information to allow people to make informed decisions during a tsunami to reduce their vulnerability (Fraser, 2014; Løvholt et al., 2014; National Research Council, 2011). This includes knowing how to interpret and respond to tsunami warnings, while also having knowledge on when, how and where to evacuate during an event. It is important that tsunami education in Banks Peninsula is targeted to both permanent residents and transient visitors which increases resilience of these populations by ensuring people can evacuate efficiently.

4.5.4.1.1 Education Campaigns

Education ensures that in a tsunami event people correctly interpret warnings and know where, when and how to evacuate, while doing so in a timely manner to reduce their risk. Becker et al. (2013) developed a comprehensive public outreach program for Hawkes Bay, which included a range of activities such as effective messages, community meetings and exercises. While the goal of this program was to improve wider resilience of the community, CCC CDEM could develop a similar program for Banks Peninsula, with a focus on tsunami education and evacuation information.

Consistent messages are already being disseminated at a national level throughout New Zealand, through various education campaigns that inform permanent residents of Banks Peninsula, as well as visitors to the area who reside in other areas of New Zealand. Campaigns such as *'Get Ready, Get Thru'* provide general information on how to prepare for a range of disasters, with additional information specific to different hazards to increase risk awareness (Get Ready, n.d). Other campaigns aim to prompt a particular action from the public. For example, the *'Long and Strong, Get Gone'* campaign aims to educate people to evacuate inland or to higher ground immediately following long and/or strong earthquake shaking (NEMA, n.d.c). In the evacuation behaviour survey, 45% (n=92) of the total respondents and 33% (n=8) of all Banks Peninsula respondents reported that they received information on the need to evacuate from CDEM (Figure 3.30). Survey respondents also identified specific education campaigns, including a respondent from Okains Bay who reported that they have since put a sign up in the Okains Bay Store window with CDEM's *'Long and Strong, Get Gone'* message. It is therefore important to continue public education campaigns and to ensure that the messages are reaching communities, including those in Banks Peninsula. This could be achieved through NEMA funding more multi-platform campaigns, as was done with the *'Long and Strong, Get Gone'* message. This message was broadcast over radio, television, and online (MCDEM, 2017c), and was highly successful in raising public awareness of evacuation following long and or strong earthquake shaking, with recognition of the *'Long and Strong, Get Gone'* phrase increasing from 83% in 2017, to 90% in 2018 (MCDEM 2018c). Survey respondents also noted that since learning of this message, their actions during a future tsunami would differ and that they would evacuate immediately, further demonstrating the effectiveness of this campaign (Section 3.4.1).

CCC CDEM could engage directly with members of Banks Peninsula communities through public meetings. While meetings could focus on explaining tsunami risk and risk management strategies – such has been done in areas of Christchurch with the changed in the evacuation zones (Healthy Christchurch, 2019), they could also create opportunities to facilitate community-led risk management strategies to further improve the efficiency of future evacuations. For example, potential evacuation routes could be created from the combination of authorities' knowledge of the hazard with local community-based knowledge. Public meetings would also allow for discussions between locals and authorities as to what other risk management strategies could be implemented to improve the efficiency of tsunami evacuations. The tsunami evacuation modelling workshops in Sumner (outlined in Section 2.3.2.3.1) allowed for this discussion, while numerous public meetings focusing on tsunami risk have been held in coastal communities of Christchurch (Schoenfeld, 2018). Public meetings would also allow for resources to be distributed to community members from authorities such as fridge magnets with preparedness checklists, or pens with key slogans to further promote tsunami preparedness and contribute to efficient evacuations. The use of public meetings would also help to improve trust between authorities and communities, further helping to improve tsunami evacuation behaviour for future evacuations.

4.5.4.1.2 Brochures and Pamphlets

Written education in the form of brochures and pamphlets is considered to be an effective method of educating the public (Mileti et al., 2004). Many communities at risk of tsunami produce pamphlets that include evacuation maps and basic tsunami awareness information to help educate the public (Siripong, 2011). This media type is useful as it provides people with something they can refer to at a later date, enabling individuals to become more interested in the topic and read the information in their own time (Mileti et al., 2004; Nathe, 2004). This would be a useful tool for Banks Peninsula communities that could increase tsunami risk awareness and improve evacuation behaviour. Brochures and pamphlets can easily be disseminated amongst people to reach both permanent and transient populations. Examples include being mailed to homes, available in public locations such as libraries or shops, or in information packages at commercial accommodation (Cole & Murphy, 2014). CCC CDEM could engage with tourism providers to ensure these resources are reaching visitors to the area. For example, brochures on tsunami risk could be left in hotel rooms for visitors to read, or could be placed at cafes. Local community members could also distribute brochures and pamphlets to new residents, similar to what the New Brighton Project offers to new community members (as outlined in Section 2.3.2.2). For media such as brochures and pamphlets to be successful, they need to include accurate scientific and technical information from reliable and credible sources, which is communicated clearly while being visually attractive (Nathe, 2004). Therefore, to be successful as an educational resource, information in this type of media should be accredited to a reliable source such as CDEM groups, CCC, ECan and/or NEMA. It is important that information included in media such as brochures and pamphlets is specific to the communities it is being disseminated in (Cole & Murphy, 2014). This allows the information to better reflect and educate people on the tsunami risk, as well as include more specifics on how they can reduce their vulnerability. The use of brochures and pamphlets would be useful in other coastal areas of New Zealand and around the world to improve tsunami risk awareness and encourage efficient evacuations during future tsunami.

4.5.4.1.3 Newsletters

Similar to brochures and pamphlets are newsletters, which are viewed as a useful tool for hazard risk education in small rural communities (Cole & Murphy, 2014). Newsletters would be a useful education tool for communities throughout Banks Peninsula. They could feature a dedicated section for tsunami risk, and include information on how to prepare for a tsunami, the type of warnings and how to appropriately respond to them, where to evacuate to, and when to return home, along with tsunami history. Primarily, this would reach permanent residents, but if printed for people to read at libraries or shops, or posted to public noticeboards, this medium would have an increased reach and would also help educate transient visitors.

4.5.4.2 Evacuation Planning

Evacuation planning aims for efficient, successful evacuations by aiding people out of exposed coastal zones to safer locations to ensure life safety (Fraser, 2014). The primary components of evacuation planning are delineating evacuation zones, safe zones, and evacuation routes (Wegscheider et al., 2010). Examples on how this information can be presented to improve the efficiency of tsunami evacuations in Banks Peninsula are discussed below.

4.5.4.2.1 Evacuation Zone Maps

Evacuation zone maps have been developed for the entire Canterbury region including communities of Banks Peninsula (see Section 2.3.2.3). These zones assist in communicating tsunami risk to the public, and assist during a response by representing areas that people will need to evacuate from (Jack & Schoenfeld, 2017; MCDEM, 2016). Evacuation zone maps are available online for individuals to access (Canterbury Maps, n.d.; CCC, n.d), enabling people to see if their home, or other areas they may spend time in, are exposed to tsunami, and additionally find where they can evacuate to in an event. During the 2016 Kaikōura tsunami evacuation it was reported by Kardos (2017) and Lane et al. (2020) that people were unaware of their evacuation zone and struggled to find this information online. To improve efficiency of future tsunami evacuations, it is crucial that this information is readily available and easily accessible. This is especially important when considering that following the 2016 evacuation only 23% (n=44) of the total survey respondents (both Christchurch and Banks Peninsula) had made the effort to identify their evacuation zone (Section 3.3.3), with only 4% (n=1) of the Banks Peninsula respondents partaking in this action. Making this information more readily available could be achieved by promoting it on local community websites, publishing images of evacuation zone maps on community noticeboards, and/or collaborating between CCC CDEM, Canterbury CDEM and Banks Peninsula community members to hold information nights to explain the tsunami zones (along with other tsunami risk management strategies).

4.5.4.2.2 Information Boards

Information boards (as displayed below in Figure 4.53) are an example of tsunami signage that provide information on an area's tsunami risk, warning systems, suggested evacuation routes, and local tsunami history (Currie et al., 2014). Information boards have been identified as an effective method of communicating tsunami risk (MCDEM, 2016), as they enable people to be educated on the risk when they arrive to the area, and therefore have the information to respond appropriately if they receive or observe a tsunami warning. It is recognised that information boards will only be successful in improving tsunami evacuation behaviour and knowledge if people acknowledge the boards and read the information presented. To reach the highest number of residents and visitors, information boards should be placed in high-use coastal areas, including beach access points, commercial holiday homes, shops, public buildings, and tourist facilities (MCDEM, 2008; MCDEM, 2016). Information boards could be installed at beach access points throughout Banks Peninsula, with smaller boards in shop fronts, public buildings or tourist facilities. They could also be implemented in areas of Christchurch, and other New Zealand and global coastal areas where they are not present. This would improve tsunami risk awareness amongst visitors and their response to tsunami warnings. The design and installation of information boards allows for collaboration between communities and emergency planners through determining where to place the boards, incorporating local knowledge on the tsunami hazard, and discussing potential evacuation routes (Fraser, 2014). It is important that the information is reviewed regularly, and updated as new information becomes available (MCDEM, 2008). For example, if tsunami evacuation zones change due to improved modelling, information board maps will need to be replaced with the most up-to-date and accurate information.

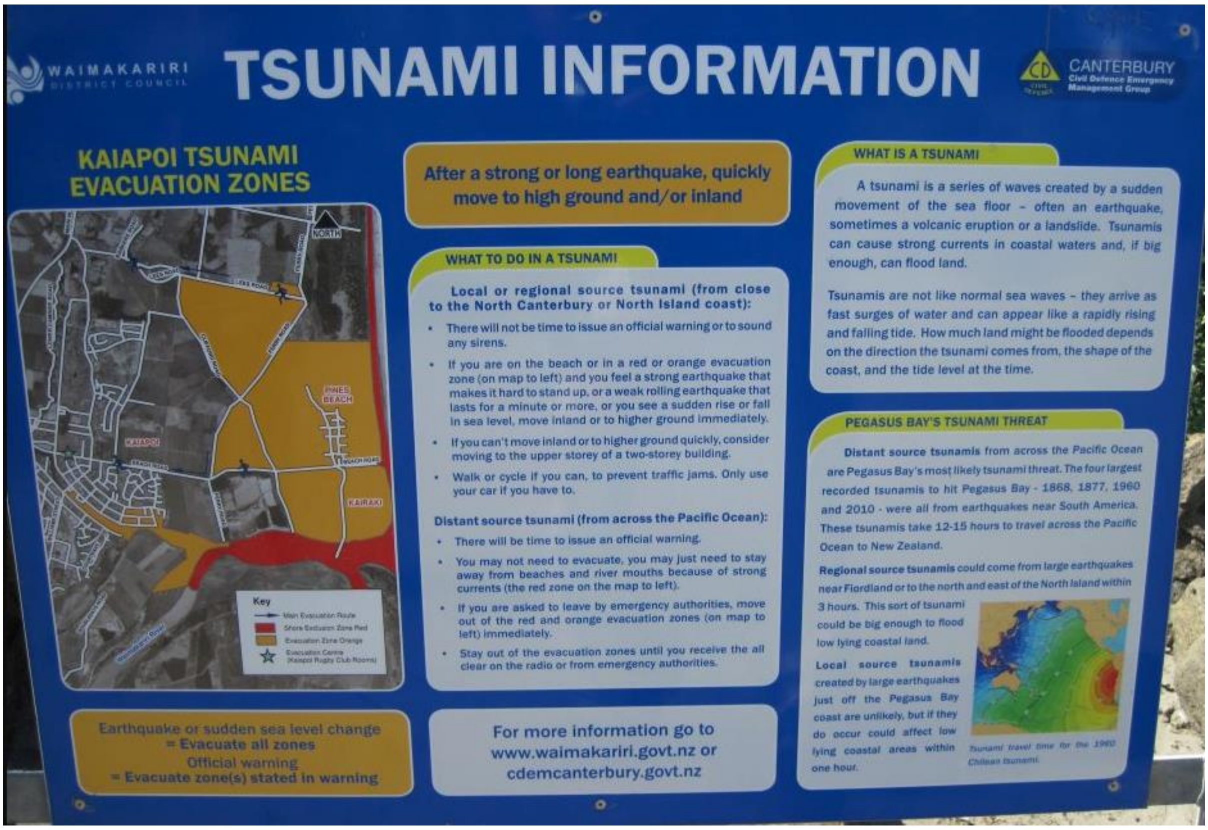

Figure 4.53: Example of a tsunami information board that has been implemented in Kairaki Beach, Kaiapoi, New Zealand (Penny, 2017).

4.5.4.2.3 Tsunami Signage

Tsunami signage identifies evacuation zones, evacuation routes, and safe zones (Fraser, 2014; see Figure 4.54). Installing tsunami signage increases public awareness prior to an event while also providing immediate guidance during an evacuation by informing people on where to evacuate to (Dengler, 2005 Lonergan et al., 2015). The installation of the signs themselves can generate local attention, further promoting tsunami evacuation planning to the public (Dengler, 2005). Tsunami signs can be linked with additional tsunami education such as the warning types that may prompt someone to follow an evacuation route (Figure 4.54). They can also feature additional information, such as the specific local evacuation zone based on the sign's spatial location, or optimal evacuation routes for specific transportation modes (such as walking or driving). Installing tsunami signage in Banks Peninsula communities would contribute to improving efficiency of future tsunami evacuations. In a study focusing on the capacity of Akaroa's infrastructure to cope with increasing tourist numbers, it was recognised that many would be first-time visitors unaware of the town's layout (Sleeman, 2008); this would likely apply to other communities throughout Banks Peninsula. Tsunami signage would therefore help inform transient visitors of the tsunami risk and evacuation safe zones. Tsunami signage would also be beneficial for encouraging local residents to identify their tsunami evacuation route and potential safe destinations. A survey respondent from Banks Peninsula expressed concern on the lack of "*advice or directions to high points*" indicating potential use of this infrastructure from residents (Appendix D). Following the 2016 tsunami evacuation, only 44% (n=11) of respondents from Banks Peninsula reported that they had discussed or identified their evacuation route and safe zone (Figure 3.28). Therefore, the placement of signage, in combination with other evacuation planning, may increase resilience towards tsunami risk by prompting more residents to plan their evacuation routes.

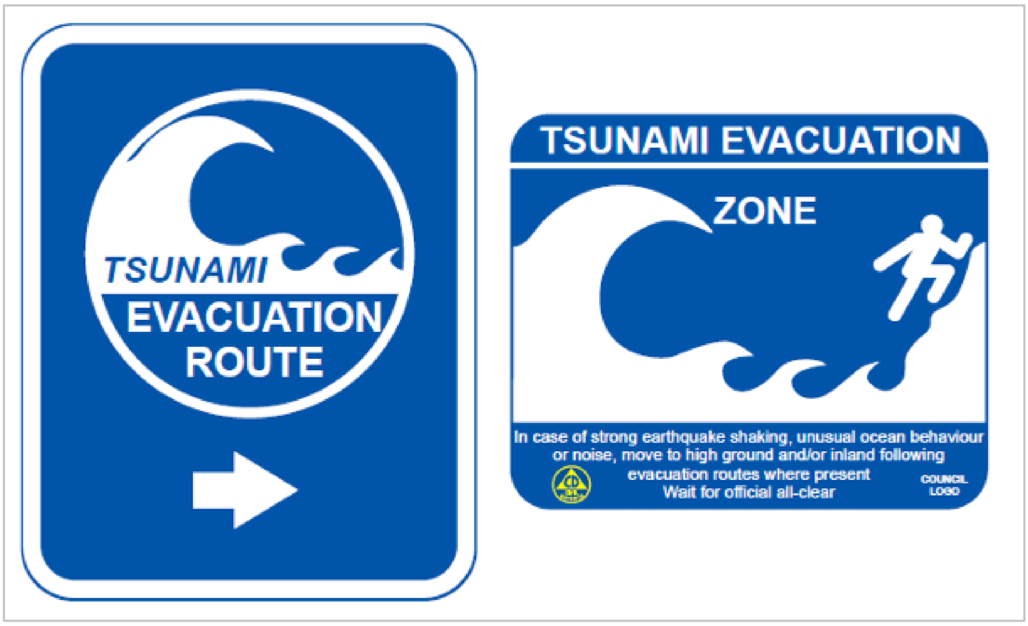

Figure 4.54: Tsunami evacuation signs (MCDEM, 2008). The sign on the left directs evacuees to safe zones; the sign on the right informs people on what tsunami evacuation zone they are in, and includes descriptions of natural warnings.

4.5.4.2.4 Blue-lines

Blue-lines represent safe places that people could evacuate to following long and/or strong earthquake shaking (WREMO, n.d.), and have been implemented throughout the Wellington region (examples shown below in Figure 4.55). The blue-lines represent the maximum inundation level of a worst case scenario (Currie et al., 2014). They have been recognised as assisting in increasing tsunami risk awareness, which could be further improved by including information signage to explain the purpose of the lines (Currie et al., 2014). Blue-lines could be implemented in areas throughout Banks Peninsula. During a tsunami evacuation they would be particularly beneficial in areas where large clusters of vehicles were observed during the field visits, such as Pigeon Bay, Okains Bay, or Akaroa, and would be useful to help educate both residents and visitors on where to evacuate during a local or regional source tsunami. Blue-lines would also encourage and assist residents in identifying tsunami evacuation routes destinations. Despite Currie et al. (2014) reporting a positive response to the implementation of the blue-lines in Wellington, it was found that some residents felt that the placement of the lines was arbitrary and there was confusion surrounding how their placement was chosen. Therefore, if blue-lines were to be implemented throughout Banks Peninsula, there would need to be community engagement to ensure local community members are aware of the purpose of this evacuation planning example, as well as why and how the placement of the lines have been chosen. People also need to be educated to evacuate beyond the blue-lines. Although there were no blue-lines in Sumner during the 2016 Kaikōura evacuation, people evacuated to higher ground, however, did not evacuate high enough (reported in evacuation survey, Appendix D). Quotes made by respondents relating to this included "*lots of people started parking a short way up the hill which slowed down traffic trying to drive past them*" and on "*Evans Pass Rd cars continued to slowly make their way up the hill as people were backlogged for ages*". While blue-lines would be a beneficial tool in improving evacuation knowledge and behaviour for both residents and visitors of Banks Peninsula and in other coastal communities, these examples highlight the need for education on the need to evacuate beyond these lines to minimize ensure that there is enough space for those following to evacuate to safer ground.

Figure 4.55: Examples of blue-lines in Wellington (Fraser, 2014). A is at the edge of the maximum inundation zone, while B is directing someone to a safe zone.

4.5.4.2.5 Evacuation Exercises

Evacuation exercises combine evacuation planning and education, and enable the public to practice their evacuation routes and identify areas that would reduce their vulnerability in a tsunami event. Within New Zealand, the national *'ShakeOut'* exercise, organised by NEMA, incorporates a tsunami hikoi and is an example of a tsunami evacuation exercise that encourages the importance of immediate self-evacuation following a natural tsunami warning, along with recognising a tsunami evacuation route (Get Ready, n.d.). Residents, schools, and community groups throughout the country, including Banks Peninsula, are encouraged to take part in this event. While evacuation exercises have been recognised as having high organisation costs and low participation rates (Kawai et al., 2015; Mundai et al., 2012; Wafda et al., 2013), in smaller tight-knit communities such as those in Banks Peninsula they may be an effective form of evacuation planning. CCC CDEM and Canterbury CDEM could facilitate the participation of communities within Banks Peninsula in the *'ShakeOut'* and tsunami hikoi event, or prominent community members within the areas of Banks Peninsula could organise the event for their communities. Participating in evacuation exercises would empower local residents to have better knowledge of their evacuation route and how to evacuate, contributing to efficient future evacuations (Takabatake et al., 2017).

4.5.5 Future Work and Research

4.5.5.1 Field Observations

Field observations were made over multiple weekends during hot summer days. The decision was made to conduct field observations in this weather to improve understanding of the peak day population to inform a maximum exposure scenario (Fraser et al., 2014). Due to time constraints, only 13 communities (combined into 10 modelling scenarios) were visited (Section 4.3.1.2.2). Future work to improve this would include conducting field observations in more areas of Banks Peninsula. This would allow for evacuation modelling to be simulated for additional communities, improving the validity of the modelling results.

Similarly, field observations could be made over multiple visits for the both the communities included in this study and additional communities. For example, at different times throughout the day, different days of the week or in different seasons. This would improve understanding of the transient populations of these communities, and allowing for the modelling to better represent spatio-temporal population changes. This would allow for additional modelling scenarios to be produced.

4.5.5.2 Origin Point Population

This research focused on a peak day exposure scenario where the visitors to the area had driven into Akaroa. To more accurately reflect the peak day population of Akaroa, future research could include cruise ship visitors. Between October and April, large cruise ships bring many passengers and crew members to Akaroa. For example, in the 2019-2020 season, the largest estimated total number of visitors entering the area via cruise ship on one day was 6,838 people (Akaroa, n.d.). While many visitors stay on board or take day trips to other areas of Canterbury, many stay in the Akaroa township, increasing the day visitor population (Sleeman, 2008). As this research focused on a vehicular evacuation model, the cruise ship population was excluded from the study due to their not having vehicular access. Whilst including cruise ship visitors was beyond the scope of this research, it is recognised that this group would increase overall tsunami risk in Akaroa township; the tourists may not know where and how to evacuate safely, and would further stress infrastructure utilised in evacuation, including welfare centres. It would therefore be beneficial for future research to include cruise ship visitors in exposure and vulnerability assessments for Akaroa.

4.5.5.3 Method of Evacuation Modelling

While a network based approach was chosen for this study, there would be merits to applying both pedestrian based and agent based modelling methods (Table 2.3) for Banks Peninsula.

A pedestrian based evacuation model could be developed for Banks Peninsula. This would be beneficial for emergency managers for the following factors:

- There may be circumstances where evacuating by vehicle may not be possible. For example, if there was a crash blocking a road out of the evacuation zone, or if a local or regional source tsunami was generated by an earthquake there could be a possibility of damage to roads and rockfall risk blocking accessibility of the roading network;
- All areas included in this study apart from Birdlings Flat, are surrounded by steep slopes that would make evacuating on foot feasible. In some areas, (such as Magnet Bay, Te Oka Bay, and Tumbledown Bay) it could be quicker to evacuate by foot up a nearby slope, rather than driving to areas outside of the evacuation zone. Further to this, as some of the roads around Banks Peninsula are narrow, it could be safer to evacuate on foot compared to driving;
- Akaroa often has a large increase in day population from the presence of cruise ship visitors (Sleeman, 2008). This would increase the peak-day exposure of the community. During an evacuation, it would be likely these visitors would evacuate by foot.

Improving this study by adopting a pedestrian based approach could incorporate these factors and improve understanding of community vulnerability to tsunami during peak exposure scenarios. The results would be valuable considering that pedestrian evacuation is the encouraged transportation method to reduce congestion and leave the roads available for more vulnerable population (including elderly) (MCDEM, 2016). Pedestrian modelling could further improve evacuation planning by identifying areas where evacuees could evacuate to on foot (Wood et al., 2018) which could identify potential areas for welfare centres to be established, while also allowing for evacuation signage to these areas to help minimise vehicle use in evacuations.

An agent based tsunami evacuation model could also be developed for Bank Peninsula. The agents in the model could be programmed with various characteristics, behaviours or rules that were reported in the survey data, allowing for the complexities of human behaviour during evacuations to be reflected in the model in a way that ArcCASPER could not fully achieve. This could allow for factors such as time delays to be better represented within the model, or could allow for different characteristics and rules to be given to the different groups evacuating. For example, permanent residents could be programmed to evacuate to certain areas, while transient visitors could be programmed to follow the local residents or try to evacuate back towards the Christchurch City area. An agent based modelling approach for Banks Peninsula would allow for a realistic evacuation model to be produced that is more accurate in terms of representing the population.

4.5.5.4 Safe Zone Destinations

In the evacuation modelling, points were selected on the road network at the border of tsunami evacuation zones. Apart from the additional evacuation modelling for Akaroa, none of the modelling included knowledge of pre-established or community recognised tsunami evacuation locations. In a tsunami evacuation, these would be places residents of Banks Peninsula communities would likely evacuate to, and it is possible visitors to the area would follow locals to these locations. Future research should include collaborating with local community members and councils to learn where community recognised tsunami evacuation locations are, which could then be incorporated into the modelling. This would help refine the safe zones and evacuation routes, while also improving understanding of where bottlenecks and congestion may occur.

4.5.5.5 Evacuation Behaviour Survey

Conducting further research on evacuation intentions would be beneficial for future evacuation modelling in Banks Peninsula. As presented in Section 3.4.8.2, evacuation intention studies are beneficial for predicting actual evacuation behaviour. Studies such as this have already been completed in areas of New Zealand. For example, Leonard et al. (2013) distributed a tsunami evacuation intention survey in Napier to gain an understanding of people's potential reactions and behaviour during local, regional and distant source tsunami. A similar survey could be distributed to households within the tsunami evacuation zone of Banks Peninsula. This knowledge would be useful for improving the accuracy of evacuation models produced in this study.

An evacuation intention study would allow for more accurate information to be collected on:

- *Evacuation intentions*. This study assumed that everyone evacuated, however, it is rare for full community compliance during an evacuation (Mas et al., 2012; Fraser et al., 2012; Wood & Schmidtlein, 2012). Survey data support this; 50% of the Banks Peninsula respondents evacuated (see Figure 3.12), increasing to 73% of the total survey respondents from Christchurch and Banks Peninsula who completed the survey (Section 3.3.2.2). While these data could be used to create a subset of CASPER origin points or points for an ABM, further data on evacuation intentions would help improve knowledge who does or does not evacuate, which could be useful for informing bottlenecks and congestion;
- *Origin-route-destination*. While modelled safe zones in Little Akaloa, Okains Bay and Akaroa were informed by evacuation destinations provided in the evacuation behaviour survey (Section 4.3.1.3.1), many areas did not have this information. Obtaining information regarding where people would evacuate from and to, along with their specific evacuation route, would improve model accuracy, while also validating the model. This would be further enhanced by addressing dynamic exposure i.e. how evacuation origins and destinations change on daily based on people's work and school patterns. Defined evacuation routes would also serve as a valuable model validation dataset.

4.6 SUMMARY

This chapter addressed Objective 3 of the thesis: Evacuation Modelling. The network analyst extension ArcCASPER was used to model tsunami evacuations for peak day, peak night and normal traffic in 10 areas of Banks Peninsula. The purpose of the evacuation model was to assess the ability of coastal communities in Banks Peninsula to reduce their tsunami risk by evacuating to safe zones. Inputs into the model were informed from a building inventory, field observations and implemented tsunami risk management strategies. Survey data (from Section 3) including the transportation type, congestion speed, safe zones and evacuation delay were integrated into the evacuation model to improve the validity of the modelling and make it more realistic.

5 SUMMARY

The aim of this Masters thesis, as outlined in Section 1.3, was to contribute to enhancing knowledge of tsunami evacuation behaviour and reactions to warnings, which can be used to directly inform evacuation planning in the case study area (Christchurch and Banks Peninsula) and globally. This has been achieved through a literature review on tsunami risk and risk management; the distribution of a survey with an analysis of the results to provide a comprehensive overview of tsunami evacuation behaviour and decision making during the 2016 Kaikōura earthquake tsunami; and the development and application of an evacuation modelling framework for remote/isolated communities exposed to tsunami, where the modelling has been informed by evacuation behaviours reported in the survey questionnaire. This research will help to refine evacuation planning to ensure that people can evacuate efficiently, thereby reducing their tsunami exposure and personal risk of injury and death.

A review of relevant data relating to tsunami risk, risk management strategies and the response to the 2016 Kaikōura Earthquake tsunami evacuation was collated. This had a focus on tsunami risk and risk management strategies for Christchurch and Banks Peninsula. A survey was developed and distributed amongst Christchurch and Banks Peninsula community members to identify behaviour and actions made during the 2016 evacuation. These results were analysed to characterise broad trends and identify influential factors in behaviours and actions. A framework was developed to model tsunami evacuations in Banks Peninsula. Where appropriate, survey data was utilized to inform the modelling. Based on the modelling results, strategies to improve future tsunami evacuations were identified.

The following conclusions can be drawn from this research:

i. There have been very few studies that provide a comprehensive overview of tsunami evacuation behaviour including the response to warnings, pre-evacuation actions, evacuation movement and the return home. This information is even more limited when considering coastal communities of New Zealand including those in Christchurch and Banks Peninsula where tsunami evacuations have been rare. Consequently there have been limited opportunities to integrate empirical tsunami behaviour data into evacuation modelling.
ii. The 2016 Kaikōura Earthquake generated a tsunami that prompted the evacuation of coastal communities of Christchurch and Banks Peninsula. A survey questionnaire was designed with geospatial science focus on evacuation dynamics to provide an overview of the entire evacuation process and improve understanding on how people reacted to the tsunami warnings and their decisions during this evacuation. This was deployed in the study area and a total of 220 surveys were completed in 21 communities throughout Christchurch and Banks Peninsula.
iii. The results from the survey questionnaire revealed the evacuation occurred in a confused warning environment that made it difficult for people to assess their risk and form an evacuation decision.

- Warning and evacuation information released by authorities during the crisis was contradictory,
- Common practice within New Zealand is that people will evacuate from coastal areas after having experienced long and/or strong earthquake shaking.

Although 94% of survey respondents felt the shaking of the Kaikōura earthquake, most did not perceive the shaking to be long or strong to prompt self-evacuation. It was not until the official warnings were released by CCC CDEM and MCDEM over the radio and social media, and through the activation of the tsunami sirens, that people evacuated. Consequently, there was a reliance on official warnings (released over the radio, social media and through the activation of the tsunami sirens) to prompt peoples evacuations.

iv. Only 10% of respondents evacuated immediately, with delays in evacuations caused by gathering household members, pets and life essentials, and seeking further official information to inform evacuation decisions.

v. Very few people evacuated using the recommended transportation methods of walking (2%) or biking (1%), while 96% of the survey respondents opted to drive. This led to congestion that was primarily observed in the denser suburbs of Christchurch.

vi. Empirical data can be incorporated into evacuation models to produce realistic evacuation simulations. Use of this within research has been limited due to the rarity of tsunami and empirical data relating to evacuation responses and behaviours.

vii. In perfect evacuation conditions, where people evacuate immediately after receiving or observing a tsunami warning and know where to evacuate to, evacuation modelling undertaken in this Masters research suggests that the maximum time to evacuate coastal areas of Banks Peninsula to reduce risk of a distant and regional tsunami risk, and potentially a local source risk is 4.69 minutes.

viii. When incorporating empirical survey data (reducing the number of safe zones, integrating an evacuation delay, and decreasing the evacuation speed) and increasing the number of evacuees, the time required for Banks Peninsula communities to evacuate increased to a maximum of 38.88 minutes. This suggests that there would still be time to evacuate and reduce risk of a distant source tsunami. However, there becomes less clearance time to evacuate for a regional source tsunami. While there are no known offshore faults off the coast of Banks Peninsula producing a low risk of a damaging local source tsunami, inundation modelling indicates that an offshore or underwater landslide could generate a local source tsunami that could inundate areas of Banks Peninsula. The increased evacuation time produced from this modelling highlights the importance of effective planning and education for prompt evacuations.

The following recommendations can be made to address the above conclusions:

i. Continue public education to ensure that people are aware of how to interpret tsunami warnings, thereby reducing the expectation and reliance on official warnings and promoting timely self-evacuation following natural warnings.
ii. During future evacuations the information being released from authorities to the public needs to be consistent. This is crucial to ensure that people trust the authorities, believe the threat and efficiently take action to reduce their risk.
iii. Future tsunami education needs to have an emphasis on preparedness actions to ensure that people have the planning in place to evacuate efficiently in future evacuations.
iv. There needs to be engagement with local communities to educate people on the value of walking or biking to evacuate, facilitate carpooling amongst neighbours and encourage people to pre-identify evacuation routes. This could be incorporated into the annual 'ShakeOut' event which encourages positive evacuation behaviour.
v. To minimise the evacuation cost in Banks Peninsula, permanent residents and visitors need to how to respond to tsunami warnings, how to evacuate and where to evacuate to. This can be achieved through education campaigns and the implementation of evacuation planning strategies including tsunami information boards or evacuation signs.

Recommendations for future research work include:

i. Conduct more evacuation behaviour surveys – The survey return rate of 12.4% was lower than anticipated. While the results of this survey make a useful contribution to this research field, they could be improved by conducting further surveys. This could be achieved through intended evacuation behaviour surveys. This form of survey is useful as it incorporates knowledge of tsunami risk, with how people believe they would react and behave during a tsunami event, helping to further improve knowledge and understanding in this field. Improving the survey methodology, by increasing the sample size and distribution rate, would improve evacuation behaviour and reaction knowledge while building a better geospatial understanding of where people evacuate.
ii. Further evacuation modelling – The ArcCASPER evacuation modelling tool was a useful tool to provide an insight into where bottlenecks may occur and provide an estimate of evacuation costs within Banks Peninsula. While evacuation survey data was incorporated through the average congestion speed, safe zones, transportation type and the average delay in evacuation, the tool itself lacked the ability to integrate the survey data in a way that represented the complexities within human behaviour during an evacuation. Recommendations for future work include adopting an agent based modelling approach, which is a recognised method for its ability to incorporate human evacuation behaviour. Utilizing an agent based modelling approach would incorporate various evacuation behaviours including transportation type, immediate vs delayed evacuations, to produce a realistic evacuation model that better represents the population.

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7 APPENDICES

Appendix A. REACTION TO THE 14TH NOVEMBER KAIKŌURA EARTHQUAKE QUESTIONNAIRE

This section includes the survey questionnaire that was distributed to houses to gain understanding of tsunami evacuation dynamics during the 2016 Kaikōura Earthquake. This survey was also distributed in an online format.

Q1. Where were you when the earthquake occurred on Monday 14th November 2016 at 12.02 a.m.? (Please be **very specific**, e.g. give the address, nearest street corner or landmark)

____

Q2. Did the earthquake wake you up? (Tick only one)

- ☐1 Yes
- ☐2 No
- ☐3 Not applicable (I was already awake)

Q3. How strong did the earthquake feel to you? (on Monday 14th November 2016 at 12.02 a.m.) (Tick only **one**)

- ☐1 Not felt
- ☐2 Heard but not felt
- ☐3 Gentle, hardly recognised as an earthquake (like light trucks passing)
- ☐4 A jolt or mild, but unmistakably an earthquake (like heavy traffic passing)
- ☐5 Moderate (could still stand up)
- ☐6 Strong/powerful (hard to stand up)
- ☐7 Violent/severe

Q4. For how long did you feel the earthquake shaking? _________ seconds (as **best** you can estimate) **OR**

- ☐1 Don't know
- ☐2 Not felt

Q5. How much damage did the earthquake do to your home? (Tick only **one**)

- ☐1 None
- ☐2 Slight
- ☐3 Moderate
- ☐4 Severe
- ☐5 Totally destroyed
- ☐6 Not applicable

Q6. What did you do after the earthquake stopped? (Please give details)

____

____

____

Q7a. Did you evacuate your home/location? (Tick only **one**) ☐1 Yes ☐2 No (skip to Q10)

Q7b. Did you evacuate more than once? (Tick only **one**) ☐1 Yes ☐2 No

Q8. If you did evacuate, was it because of a possible tsunami? (Tick only **one**) ☐1 Yes (skip to Q11) ☐2 No

Q9. If not because of a possible tsunami, why did you evacuate? (Please give details)

____

____

____

Q10. If you did not evacuate, why not? (Please give details)

____

____

____

Q11. What warned you of a possible tsunami coming? (Tick all that apply)

- ☐1 The earthquake (natural warning)
- ☐2 Other household/family members
- ☐3 Other community members
- ☐4 Emergency services (e.g. Police, Fire Service)
- ☐5 Official warning from Civil Defence (on social media, radio, TV…)
- ☐6 Tsunami sirens
- ☐7 Other (please describe)
- ☐8 I never thought/ have never been aware there could be a tsunami

____

Q12. What sources of information did you use to decide to evacuate or not? (Tick all that apply)

- ☐1 The earthquake (natural warning)
- ☐2 Other household/family members
- ☐3 Other community members
- ☐4 Emergency services
- ☐5 Official warning from Civil Defence (on social media, radio, TV…)
- ☐6 Other (please describe)

____

Q13. What was the MAIN reason that made you decide to evacuate? (Tick only one)

- ☐1 The earthquake (natural warning)
- ☐2 Other household/family members
- ☐3 Other community members
- ☐4 Emergency services
- ☐5 Official warning from Civil Defence (on social media, radio, TV…)
- ☐6 Other (please describe)
- ☐7 Not applicable

____

Q14. What did you do before evacuating? (Tick all that apply)

- ☐1 Nothing (evacuated immediately)
- ☐2 Gathered family/household members
- ☐3 Gathered life essentials (food, water…)
- ☐4 Collected valuables (jewellery, money etc.)
- ☐5 Called family or friends
- ☐6 Assisted others in evacuation (e.g. friends or neighbours)
- ☐7 Sought further official information (from radio, TV, internet)
- ☐8 Discussed action plan with family/other community members
- ☐9 Gathered my pets
- ☐10 Other (please describe)
- ☐11 Not applicable

____

Q15. How long did all of these actions take, before you actually started evacuating? (Tick only one)

- ☐1 One minute or less
- ☐2 1-10 minutes
- ☐3 10-30 minutes
- ☐4 30 minutes-1 hour
- ☐5 1-3 hours
- ☐6 Longer than 3 hours
- ☐7 Not applicable

Q16. What time did you evacuate?

____

Q17. Where did you evacuate to? (Please be **<u>very specific</u>**, e.g. give the address, nearest street corner or landmark)

____

Q18. Once you started evacuating, how long did it take to reach your destination? _______ minutes (as **<u>best</u>** you can estimate)

Q19. How did you travel to your evacuation destination? (Tick only one)

- ☐1 Car
- ☐2 Foot
- ☐3 Public transportation
- ☐4 Bicycle or similar
- ☐5 Other (please describe) ______________________________
- ☐6 Not applicable

Q20. Were you in need of any assistance for evacuating? (Tick only one)

- ☐1 Yes (please describe) ____
- ☐2 No (skip to Q20)
- ☐3 Not applicable

Q21. If yes, how did this affect the evacuation process? (Tick only one)

- ☐1 I received the support I needed
- ☐2 It delayed the evacuation, but I evacuated anyway
- ☐3 It was a barrier so I did not evacuate

Q22. How long did you stay at your evacuation point? ________ hours _______ minutes (as **best** you can estimate)

Q23. Why did you decide to return from your evacuation point? (Tick all that apply)

- ☐1 When I felt it was safe (after seeing evidence that there was no danger)
- ☐2 After discussing with others
- ☐3 After a reasonable time
- ☐4 When I received an official 'All Clear' message
- ☐5 Other (please describe) ____
- ☐6 Not applicable

Q24. What is your gender? (Tick only one)

- ☐1 Male
- ☐2 Female
- ☐3 Gender diverse
- ☐4 Prefer not to disclose

Q25. In what year were you born? ______________ **or** ☐ Prefer not to disclose

Q26. Which best describes the situation you are living in? (Tick only one)

- ☐1 Family with children
- ☐2 Family without children
- ☐3 Alone
- ☐4 With non-family
- ☐5 Prefer not to disclose

Q27. Please draw your evacuation route on the map:

Q28. Did you encounter any traffic congestion or were you aware of congestion problems? ☐1 Yes ☐2 No (skip to Q.30)

Q29. If yes, which roads or areas were congested? Please indicate these roads and areas on the map

____

____

____

____

Q30. On average, how slow do you think traffic was moving in these congested areas? __________ km/h (as **best** you can estimate)

Q31. How long were these roads or areas congested for? From __________a.m. until ______ a.m. (as **best** you can estimate).

Q32. Did you observe stages/surges of evacuation traffic? At what times did these occur?

Q33. Do you have any other comments about the evacuation?

Q34. Prior to the Monday 14th November 2016 Earthquake, how would you describe your knowledge of tsunami hazards and the need to evacuate? (Tick only **one**)

- ☐1 Non-existent
- ☐2 Very poor
- ☐3 Poor
- ☐4 Fair
- ☐5 Good
- ☐6 Very good

Q35. If you were aware prior to the 14th November 2016 Earthquake of tsunami hazards and the need to evacuate, what were your information sources? (Tick **all** that apply)

- ☐1 I was not aware of tsunami hazards and the need to evacuate
- ☐2 Civil Defence information (e.g. back of phone book, pamphlets)
- ☐3 Formal education – primary/intermediate school
- ☐4 Formal education – secondary school
- ☐5 Formal education – tertiary education (university/polytechnic)
- ☐6 Media coverage of previous tsunamis (e.g. 2004 Boxing Day Tsunami, 2011 Japan Tsunami)
- ☐7 Documentaries (television or movies)
- ☐8 Books, or articles in magazines/newspapers
- ☐9 Public information sessions - Civil Defence
- ☐10 Public information sessions - Other
- ☐11 Discussions with Civil Defence Staff
- ☐12 Discussions with family and friends
- ☐13 Other (please describe)

Q36. How did your prior awareness of tsunami hazards influence your behaviour BEFORE the 14th November 2016 Earthquake? (Tick **all** that apply)

- ☐1 I had discussed/prepared an evacuation plan for my family/household
- ☐2 I had prepared a go-bag
- ☐3 I had arranged to check on my neighbours
- ☐4 I had prepared an emergency kit
- ☐5 It did not influence my behaviour
- ☐6 Other (please describe)

Q37. Did your prior awareness of tsunami hazards influence your behaviour AFTER the 14th November 2016 Earthquake? (Tick only **one**)

- ☐1 Yes
- ☐2 No
- ☐3 Not applicable

Q38. How did your prior awareness of tsunami hazards influence your behaviour AFTER the 14th November 2016 Earthquake? (Tick **all** that apply)

- ☐1 It did not influence my behaviour
- ☐2 Moved to higher ground
- ☐3 Moved inland/away from beach
- ☐4 Gathered essential items before evacuating
- ☐5 Alerted or check on family/friends/neighbours
- ☐6 Listened to radio for further information
- ☐7 Monitored websites (e.g. GeoNet, Civil Defence, City Council) for further information
- ☐8 Monitored social media (e.g. Facebook, Twitter) for further information
- ☐9 Other (please describe)

____

Q39. Following the 14th November 2016 Earthquake, how would you describe your knowledge of tsunami hazards and the need to evacuate NOW? (Tick only **one**)

- ☐1 Non-existent
- ☐2 Very poor
- ☐3 Poor
- ☐4 Fair
- ☐5 Good
- ☐6 Very good

Q40. Which of the following preparations have you made in case of another significant earthquake and tsunami evacuation? (Tick **all** that apply)

- ☐1 I have made no preparations
- ☐2 Discussed evacuation plan with family/household members
- ☐3 Arranged to check on neighbours to ensure they are aware of evacuation
- ☐4 Prepared a go-bag containing essential items
- ☐5 Identified evacuation routes/destinations
- ☐6 Made yourself aware of evacuation zone information (e.g. through Christchurch City Council Website)
- ☐7 Ensured easy access to online information updates (e.g. bookmarked Civil Defence website on your phone)
- ☐8 Prepared an emergency kit with essential supplies (e.g. food and water for 3 days)
- ☐9 Other (please describe)

____

Appendix B. Survey Distribution Footprint

This section presents aerial photographs of the communities where surveys were distributed. The yellow lines represent streets where surveys were distributed. Included in the caption for each figure is the distribution rate.

Figure 7.1: Survey distribution footprint for Akaroa. The distribution rate was every household.

Figure 7.2: Survey distribution footprint for Teddington. The distribution rate was every household.

Figure 7.3: Survey distribution footprint for Le Bons Bay. The distribution rate was every household.

Figure 7.4: Survey distribution footprint for Birdlings Flat. The distribution rate was every household.

Figure 7.5: Survey distribution rate for Little Akaloa. The distribution rate was every household.

Figure 7.6: Survey distribution footprint for Lyttleton. The survey distribution rate was every 7th household.

Figure 7.7: Survey distribution footprint for Mount Pleasant. The survey distribution rate was every 7th household.

Figure 7.8: Survey distribution footprint for New Brighton. The survey distribution rate was every 7th household.

Figure 7.9: Survey distribution footprint for North Brighton. The distribution rate was every 7th household.

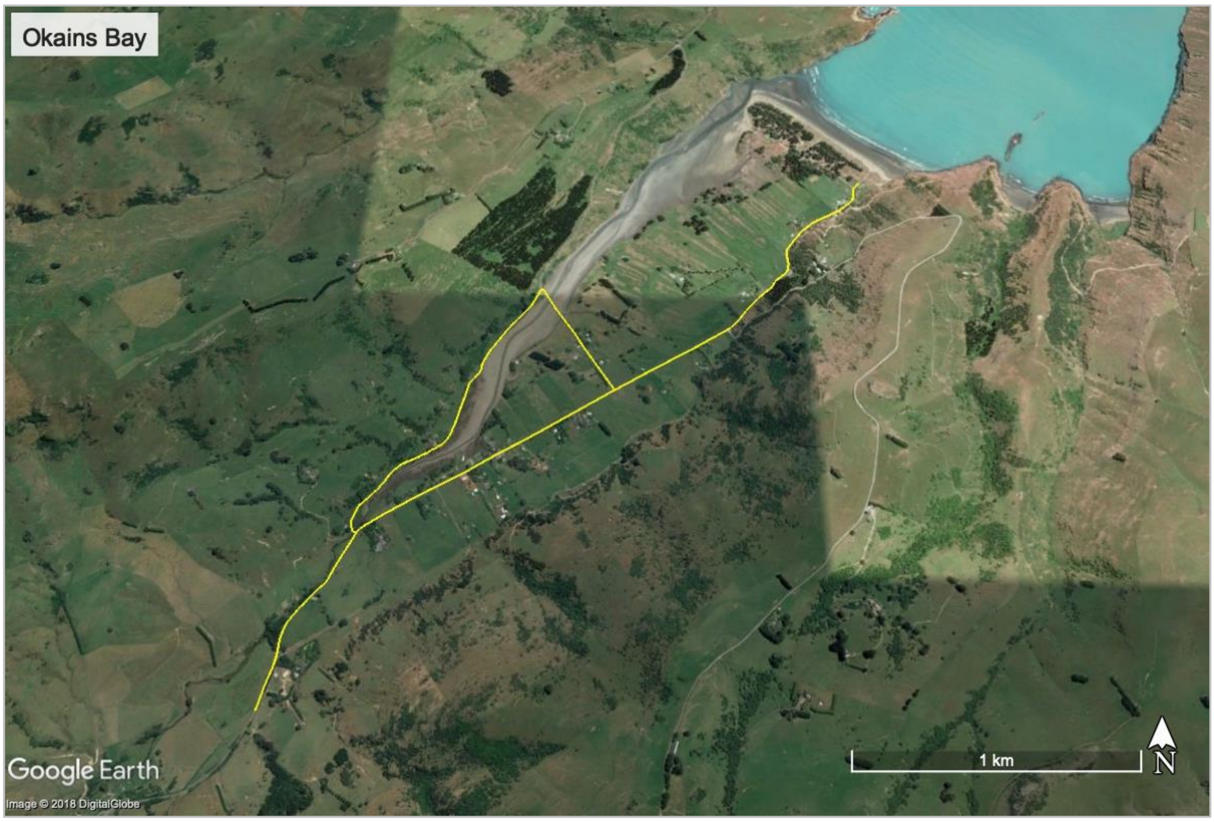

Figure 7.10: Survey distribution footprint for Okains Bay. The survey distribution rate was every household.

Figure 7.11: Survey distribution footprint for Redcliffs. The survey distribution rate was every 7th household.

Figure 7.12: Survey distribution footprint for South Brighton. The survey distribution rate was every 7th household.

Figure 7.13: Survey distribution footprint for Southshore. The survey distribution rate was every 7th household.

Figure 7.14: Survey distribution footprint for Sumner. The survey distribution rate was every 3rd household.

Appendix C. Ethics Approval

This section provides the letters sent from the Human Ethics Committee approving the project and the survey distribution. Two approvals were sought – the first focuses on the survey distribution for Sumner, while the second focuses on the wider survey area.

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2017/29/LR-PS

11 September 2018

Thomas Wilson
Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Thomas

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Comparison of Sumner Tsunami Evacuation Modelling with the Evacuation Dynamics that Occurred During the 2016 Kaikoura Tsunami Event".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your emails of 28th May and 7th and 29th August 2018.

With best wishes for your project.

Yours sincerely

R. Robinson
pp.

Professor Jane Maidment
Chair, Human Ethics Committee

Figure 7.15: Ethics approval for Sumner survey.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2018/42/LR-PS

15 October 2018

Thomas Wilson
Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Thomas

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Eastern Christchurch and Banks Peninsula Tsunami Risk Perception and Evacuation Dynamics that Occurred During the 2016 Kaikōura Tsunami Event".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 8th October 2018.

With best wishes for your project.

Yours sincerely

pp. R. Robinson

Professor Jane Maidment
Chair, Human Ethics Committee

Figure 7.16: Ethics approval for survey of communities in Christchurch and Banks Peninsula.

Appendix D. SURVEY RESULTS

This section provides the full results of the evacuation behaviour survey. The demographics are presented first, followed by the remaining survey results. The survey results follow the outline of the survey.

a. Demographic characteristics

More than half of the surveys that were returned were completed by people who identify as female in both Banks Peninsula (69%, n=18) and Christchurch (61%, n =105) (Table 7.1).

Table 7.1: Gender (n=199)

Gender	Banks Peninsula	Christchurch
Female	69% (n=18)	61% (n=105)
Male	27% (n=7)	39% (n=68)
Gender diverse	4% (n=1)	0% (n=0)
Total	100% (n=26)	100% (n=173)

The age range of people who completed the survey ranged from 28 to 88 years old (Table 7.2). The average age of respondents from Banks Peninsula was 58, while for Christchurch was 56.

Table 7.2: Age at time of survey (n=176). In brackets is the year respondents were born

Age	Banks Peninsula (n=25)	Christchurch (n=151)
Oldest	82 (1936)	88 (1930)
Youngest	34 (1984)	28 (1990)
Average	58 (1960)	56 (1962)

Forty-two percent (n=11) of respondents from Banks Peninsula lived in a family with children (Table 7.3). A similar proportion of respondents from Christchurch also reported living in a family with children (40%, n=69) (Table 7.3). Some respondents did note that they were living with pets.

Table 7.3: Living Situation (n=197)

Living situation	Banks Peninsula	Christchurch
Family with children	42% (n=11)	40% (n=69)
Family without children	27% (n=7)	36% (n=61)
Alone	27% (n=7)	19% (n=32)
With non-family	0% (n=0)	5% (n=8)
Prefer not to disclose	4% (n=1)	1% (n=1)
Total	100% (n=26)	100% (n=171)

b. Reactions to the Kaikōura Earthquake and Tsunami Evacuation

i. Were Participants Woken

Only 4% (n=1) of respondents from Banks Peninsula and 6% (n=11) from Christchurch did not feel the shaking from the Kaikōura Earthquake (Table 7.4).

Table 7.4: Woken by earthquake (n=208)

Were you woken by the Kaikōura earthquake	Banks Peninsula	Christchurch
Yes	78% (n=21)	80% (n=145)
No	4% (n=1)	6% (n=11)
Not applicable (already awake)	19% (n=5)	14% (n=25)
Total	100% (n=27)	100% (n=181)

ii. Earthquake Shaking Intensity and Duration

Shown in Table 7.5, more than half of the respondents from Banks Peninsula perceived the shaking during the Kaikōura earthquake to be of a moderate intensity (56%, n=15). A similar proportion of respondents from Christchurch also felt the shaking to be of a moderate intensity (58%, n=105) (Table 7.5). There were no respondents from either Banks Peninsula or Christchurch who heard but did not feel the earthquake shaking.

Table 7.5 Earthquake shaking intensity (n=208)

How strong did the Kaikōura Earthquake feel to you?	Banks Peninsula	Christchurch
Not felt	4% (n=1)	3% (n=5)
Heard but not felt	0% (n=0)	0% (n=0)
Gentle	0% (n=0)	2% (n=4)
A jolt or mild	22% (n=6)	11% (n=20)
Moderate	56% (n=15)	58% (n=105)
Strong/powerful	7% (n=2)	21% (n=38)
Violent/severe	11% (n=3)	5% (n=9)
Total	100% (n=27)	100% (n=181)

The perceived shaking duration ranged between 2.5 and 240 seconds (Table 7.6). The average shaking duration perceived from respondents from Banks Peninsula was 59.12 seconds, while for Christchurch was 29.59 seconds. Thirty-three percent (n=9) of respondents from Banks Peninsula and 19% (n=34) from Christchurch did not know how long they though the shaking lasted for (Table 7.7).

Table 7.6: Earthquake shaking duration in seconds (n=159)

Shaking duration	Banks Peninsula (n=17)	Christchurch (n=142)
Minimum	6 seconds	2.5 seconds
Maximum	180 seconds	240 seconds
Average	59.12 seconds	53.65 seconds

Table 7.7 Earthquake shaking duration (n=48)

Shaking duration	Banks Peninsula	Christchurch
Don't know	33% (n=9)	19% (n=34)
Not felt	4% (n=1)	2% (n=4)
Total	37% (n=10)	23% (n=38)

iii. Damage to House

Eighty-five percent (n=23) of respondents from Banks Peninsula and 71% (n=125) from Christchurch experienced no damage to their house from the Kaikōura earthquake (Table 7.8). Four percent (n=7) respondents from Christchurch reported that they experienced moderate damage to their house (Table 7.8).

Table 7.8: Damage to house (n=202)

How much damage did the Kaikōura earthquake do to your house?	Banks Peninsula	Christchurch
None	85% (n=23)	71% (n=125)
Slight	15% (n=4)	25% (n=43)
Moderate	0% (n=0)	4% (n=7)
Severe	0% (n=0)	0% (n=0)
Totally destroyed	0% (n=0)	0% (n=0)
Total	100% (n=27)	100% (n=175)

c. Actions after Earthquake

Respondents were asked to explain what they did after the earthquake shaking had stopped. Similar responses have been grouped into categories.

Banks Peninsula:

- Went back to sleep (n=5),
- Looked for further information on social media, the radio, TV, from GeoNet/GNS Science and local or national authorities (n=11),
- Check household members or contact others (n=9),
- Check outside (n=1),

- Evacuate (n=3),
- Locate emergency items (n=1).

Christchurch:

- Went back to sleep (n=38),
- Looked for further information on social media, the radio, TV, from GeoNet/GNS Science and local or national authorities (n=86),
- Check household members or contact others (n=44),
- Check outside (n=2),
- Evacuate (n=9),
- Locate emergency items (n=10),
- Check the house for damage (n=8),
- Check pets (n=6).

d. Evacuation Decision

Of the total 220 responses, 144 respondents recorded that they evacuated their homes at some point during the 2016 Kaikōura earthquake tsunami (Table 7.9). This gives an evacuation rate of 65%. An additional 17 respondents either stated that they did not evacuate or left the question blank, however answered the remainder of the survey as if they had evacuated. Including these responses brings the total number of respondents who evacuated to 161, giving an evacuation rate of 73%.

In Banks Peninsula 50% (n=13) of respondents did not evacuate (Table 7.10). Reasons for not evacuating included:

- Not having transport (n=1),
- Living far from the sea or up a hill (n=4),
- Location of the earthquakes epicentre (n=1),
- Did not perceive there to be a tsunami risk (n=2).

In Christchurch 17% (n=31) of respondents did not evacuate (Table 7.10). Reasons for not evacuating included:

- Given the earthquake shaking did not perceive there to be a risk (n=6)
- Not having transport (n=1),
- Living far from the sea or up a hill (n=14),
- Absence of tsunami sirens (n=7),
- Initial message of no tsunami threat (n=2),
- Did not experience damage to house (n=3),
- Not having transport (n=1),
- Did not feel safe to leave their house (for crime and burglary) (n=1),

- Location of the earthquakes epicentre (n=4).

Table 7.9: Number of people who evacuated (n=204)

Did you evacuate?	Banks Peninsula	Christchurch
Yes	42% (n=11)	75% (n=133)
No	58% (n=15)	25% (n=45)
Total	100% (n=26)	100% (n=178)

Table 7.10: Revised number of people who evacuated (including the respondents who left this question blank or answered no, but then answered the remainder of the survey to imply they did evacuate) (n=205).

Did you evacuate?	Banks Peninsula	Christchurch
Yes	50% (n=13)	83% (n=148)
No	50% (n=13)	17% (n=31)
Total	100% (n=26)	100% (n=179)

A small proportion of respondents evacuated multiple times during this evacuation. Shown in Table 7.11, this consisted of 6% (n=1) of Banks Peninsula respondents and 9% (n=11) of respondents from Christchurch. These respondents stated that they evacuated directly after the earthquake, but were advised of no tsunami threat so returned home, only to evacuate again once the sirens had been sounded. People also returned home after the sirens had stopped, but re-evacuated when the sirens sounded again.

Table 7.11: Number of people who evacuated more than once (n=143)

Did you evacuate more than once?	Banks Peninsula	Christchurch
Yes	6% (n=1)	9% (n=11)
No	94% (n=15)	91% (n=116)
Total	100% (n=16)	100% (n=127)

Twenty-one percent (n=3) of respondents from Banks Peninsula evacuated in this event for reasons other than the tsunami risk (Table 7.12). These reasons included:

- Role as a Civil Defence Sector Warden (n=1),
- To check on family in Christchurch (n=1).

Five percent (n=7) of respondents from Christchurch evacuated for reasons other than the tsunami risk itself (Table 7.12). These reasons included:

- The sirens (including to escape the sound) (n=6),
- Police knocking on doors and telling people to leave (n=1).

Table 7.12: Reason for evacuation (n=146)

Did you evacuate because of a possible tsunami?	Banks Peninsula	Christchurch
Yes	79% (n=11)	95% (n=125)
No	21% (n=3)	5% (n=7)
Total	100% (n=14)	100% (n=132)

e. Information and Warning Sources

i. Warning Sources

Respondents were able to select all of the warning sources that warned them of a possible tsunami.

Most of the respondents from Banks Peninsula relied on either the natural warning of the earthquake shaking (33%, n=11) and official warnings from Civil Defence (33%, n=9), while 44% (n=12) were warned from other sources (Table 7.13). This included:

- Family and friends living elsewhere (n=4),
- The isolation of Banks Peninsula communities including poor radio and cellphone reception meant people reported that they did not use any warning sources (n=3).

Shown in Table 7.13, respondents from Christchurch most commonly recognised the tsunami sirens (47%, n=84), earthquake as a warning source of the tsunami (38%, n=68) and other official warnings from Civil Defence (34%, n=60). Other warning sources recognised by respondents from Christchurch included:

- Family and friends living elsewhere (n=11),
- Observing neighbours and cars leaving the area (n=2),
- Radio or social media (n=11).

Table 7.13: Tsunami warning sources (n=205)

What warned you of a possible tsunami coming?	Banks Peninsula (n=27)	Christchurch (n=178)
The earthquake (natural warning)	33% (n=11)	38% (n=68)
Other household/family members	4% (n=1)	15% (n=27)
Other community members	4% (n=1)	18% (n=32)
Emergency services	4% (n=1)	13% (n=23)
Official warning from Civil Defence	33% (n=9)	34% (n=60)
Tsunami sirens	4% (n=1)	47% (n=84)
Other	44% (n=12)	21% (n=37)
Never thought there could be /not aware of tsunami risk	15% (n=4)	3% (n=5)

ii. Information Sources

Respondents were also asked to select all of the information sources that informed their evacuation decision.

Shown in Table 7.14, information sources recognised by Banks Peninsula respondents included the earthquake (33%, n=9), official warnings from Civil Defence (41%, n=11) and other sources (48%, n=13) including:

- Local knowledge (n=1),
- Did not perceive there to be a risk (n=2).

Information sources recognised by Christchurch respondents, shown in Table 7.14, included the earthquake (36%, n=63), official warnings from Civil Defence (50%, n=88) and other household and family members (42%, n=24) including:

- Tsunami sirens (n=21),
- Media, internet, radio (including GeoNet) (n=11).

Table 7.14 Information used in evacuation decision (n=204)

What sources of information did you use when deciding whether to evacuate?	Banks Peninsula (n=27)	Christchurch (n=177)
The earthquake (natural warning)	33% (n=9)	36% (n=63)
Other household/family members	11% (n=3)	42% (n=24)
Other community members	7% (n=2)	34% (n=19)
Emergency services	4% (n=1)	8% (n=15)
Official warning from Civil Defence	41% (n=11)	50% (n=88)
Other	48% (n=13)	32% (n=57)

iii. Main Warning Source

Respondents were asked to give the main reason for them to evacuate (summarised in Table 7.15). The main reasons that made people to evacuate in Birdlings Flat were the natural warning of the earthquake (40%, n=6) and official warnings from Civil Defence (33%, n=5). The main warning sources that made respondents from Christchurch evacuate were Official warnings from Civil Defence (28%, n=42) and other reasons (28%, n=41) including:

- Tsunami sirens (n=26).

Table 7.15: Main reason to evacuate (n=164)

What was the main reason that made you evacuate?	Banks Peninsula	Christchurch
The earthquake (natural warning)	40% (n=6)	23% (n=34)
Other household/family Members	7% (n=1)	15% (n=10)
Other community members	0% (n=0)	10% (n=15)
Emergency services	7% (n=1)	1% (n=2)
Official warning from Civil Defence	33% (n=5)	28% (n=42)
Other	13% (n=2)	28% (n=41)
Total	100% (n=15)	100% (n=149)

f. Actions before Evacuating

Survey respondents were asked to identify all of the actions that they took prior to evacuating.

The main actions undertaken by respondents from Banks Peninsula, shown in Table 7.16, included gathering household and family members (40%, n=6), gathering pets (33%, n=5) and discussing the action plan with others (33%, n=5). Other actions undertaken by Banks Peninsula respondents included:

- Listening to radio and texts on the radio from others affected (n=1).

Table 7.16 shows the main actions undertaken by respondents from Christchurch included gathering household and family members (49%, n=75), gathering pets (37%, n=56) and seeking further official information (26%, n=40). Other actions were undertaken by 37% (n=56) of respondents and included:

- Checked emergency generator and power systems (n=1),
- Went back to sleep (n=2),
- Checked on neighbours (n=1),
- Gathered items such as clothes, baby gear, passports, medication (n=8),
- Collect neighbours who have no transport (n=1),
- Watched the tides (n=1).

Table 7.16: Actions before evacuating (n=168)

What did you do before evacuating?	Banks Peninsula (n=15)	Christchurch (n=153)
Nothing (evacuated immediately)	0% (n=0)	11% (n=17)
Gathered family/household members	40% (n=6)	49% (n=75)
Gathered life essentials	20% (n=3)	31% (n=48)
Collected valuables	7% (n=1)	20% (n=30)
Called family or friends	13% (n=2)	33% (n=51)
Assisted others in evacuation	7% (n=1)	18% (n=28)
Sought further official information	20% (n=3)	41% (n=63)
Discussed action plan with family/other community members	33% (n=5)	26% (n=40)
Gathered my pets	33% (n=5)	37% (n=56)
Other	13% (n=2)	37% (n=56)

As shown in Table 7.17, respondents from Banks Peninsula generally took between 10-30 minutes to get their things ready to evacuate (43%, n=6), while respondents form Christchurch generally took between 1-10 minutes to get ready to evacuate (38%, n=56).

Table 7.17: Time to get ready before evacuating (n=161)

How long did it take before you started to evacuate?	Banks Peninsula	Christchurch
<1 Minute	7% (n=1)	1% (n=1)
1 - 10 Minutes	29% (n=4)	38% (n=56)
10 - 30 Minutes	43% (n=6)	30% (n=44)
30 Minutes - 1 Hour	7% (n=1)	15% (n=22)
1 - 3 Hours	7% (n=1)	16% (n=23)
>3 Hours	7% (n=1)	1% (n=1)
Total	100% (n=14)	100% (n=147)

g. Evacuation Dynamics

i. Evacuation Time

The earliest evacuation time was approximately 12:10 a.m. which coincides with evacuating as soon as the earthquake had occurred (Table 7.18). The latest time to evacuate was approximately 3:07 a.m (Table 7.18). Twenty-one respondents explicitly stated that they evacuated after the tsunami sirens were activated. Twenty-seven respondents could not remember their time of evacuation. Note that in this question respondents often gave a range of times when this occurred, the median of the timeframe was used. For example, a respondent estimated they began their evacuation between 3:00-3:15 a.m., with the median time of 3:07 a.m. used for the results below.

Table 7.18: Time of evacuation

Approximately when did you evacuate?	Banks Peninsula	Christchurch
Minimum	12:15 a.m.	12:10 a.m.
Maximum	2:30 a.m.	03:07 a.m.

It took between 2 and 120 minutes for respondents to reach their evacuation point (Table 7.19). The average time to reach an evacuation point was 18.43 minutes in Banks Peninsula and 23.32 minutes in Christchurch.

Table 7.19: Time to reach evacuation destination

How long did it take you to reach your evacuation destination?	Banks Peninsula	Christchurch
Minimum	3 minutes	2 minutes
Maximum	35 minutes	120 minutes
Average	18.43 minutes	23.32 minutes

Table 7.20 shows the transportation methods used during the 2016 evacuation. All of the survey respondents from Banks Peninsula reported that they evacuated in a car during this event (100%, n=14). The majority of respondents from Christchurch also reported that they evacuated in a car (96%, n=142). Other transportation methods were used by 1% (n=1) of Christchurch respondents including:

- Motorscooter (n=1).

Table 7.20: Method of transportation to the evacuation point (n=162)

How did you travel to your evacuation destination?	Banks Peninsula	Christchurch
Car	100% (n=14)	96% (n=142)
Foot	0% (n=0)	3% (n=4)
Public transport	0% (n=0)	0% (n=0)
Bicycle or similar	0% (n=0)	1% (n=1)
Other	0% (n=0)	1% (n=1)
Total	100% (n=14)	100% (n=148)

ii. Evacuation Routes

Respondents were asked to document their location during the earthquake, and where they evacuated to (Questions 1 and 17). They were also asked to give a detailed description of which roads they used to evacuate, and to draw the route on the map provided in the survey (Question 27). For those answers without descriptions of roads taken, or lacking routes drawn on the map provided, assumptions were made based on the quickest route to get to the destination given.

Out of the total 220 responses recorded, 151 evacuation paths were documented. This included 13 evacuation routes form Banks Peninsula and 138 from Christchurch. Figure 7.17 provides an overview of all of the evacuation routes, with insets of the Coastal Ward, Heathcote Ward and Banks Peninsula Ward. Figure 7.18 and Figure 7.19 presents evacuation routes for the Coastal Ward (North Brighton, New Brighton, South Brighton and Southshore). Evacuation route maps for the Heathcote Ward (Sumner, Redcliffs and Mt Pleasant) are shown in Figure 7.20 and Figure 7.21. Evacuation routes for Banks Peninsula included Akaroa, Birdlings Flat, Le Bons Bay, Little Akaloa and Okains Bay, and are shown in Figure 7.22.

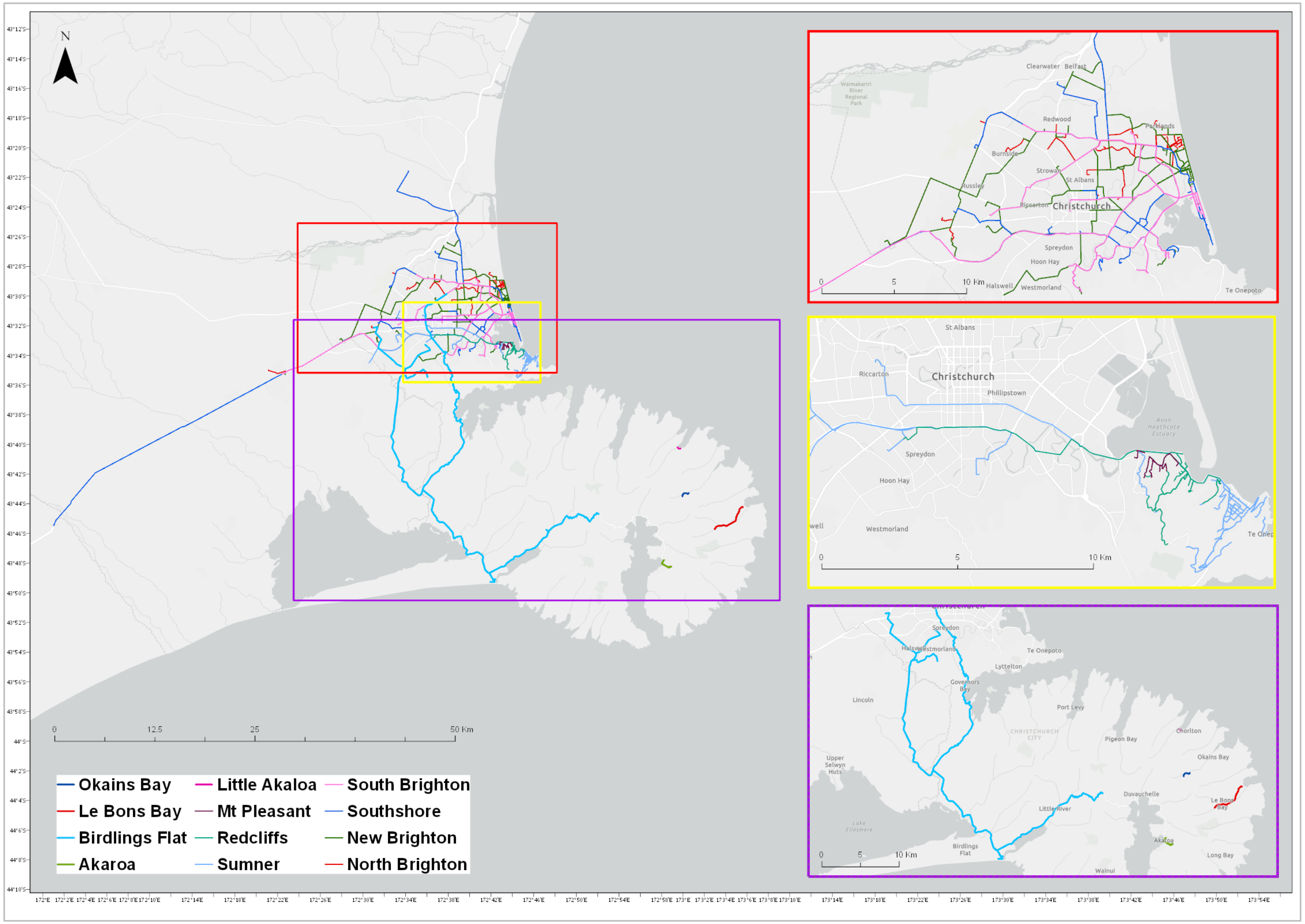

Figure 7.17: Evacuation routes for Banks Peninsula and Christchurch. Insets are included for the Coastal Ward, Heathcote Ward and Banks Peninsula Ward.

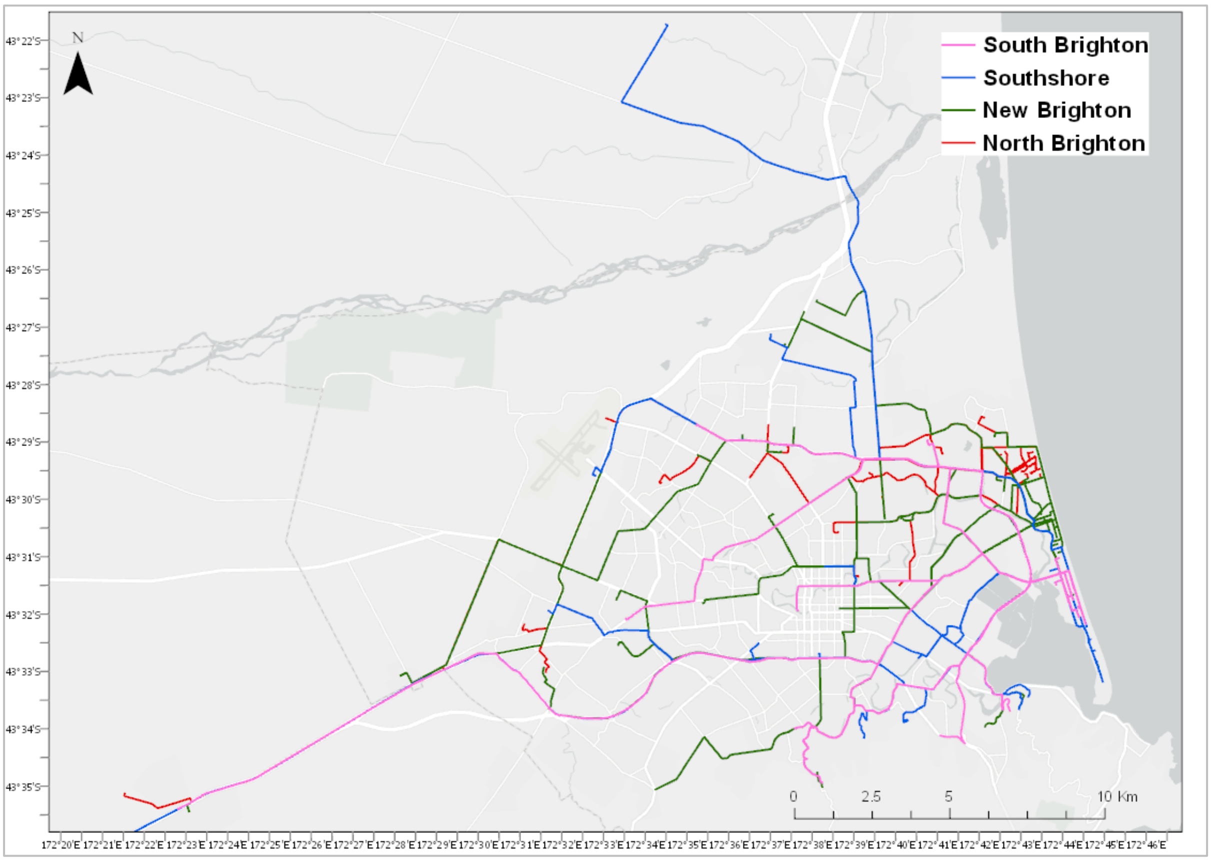

Figure 7.18: Evacuation routes focusing on the Coastal Ward.

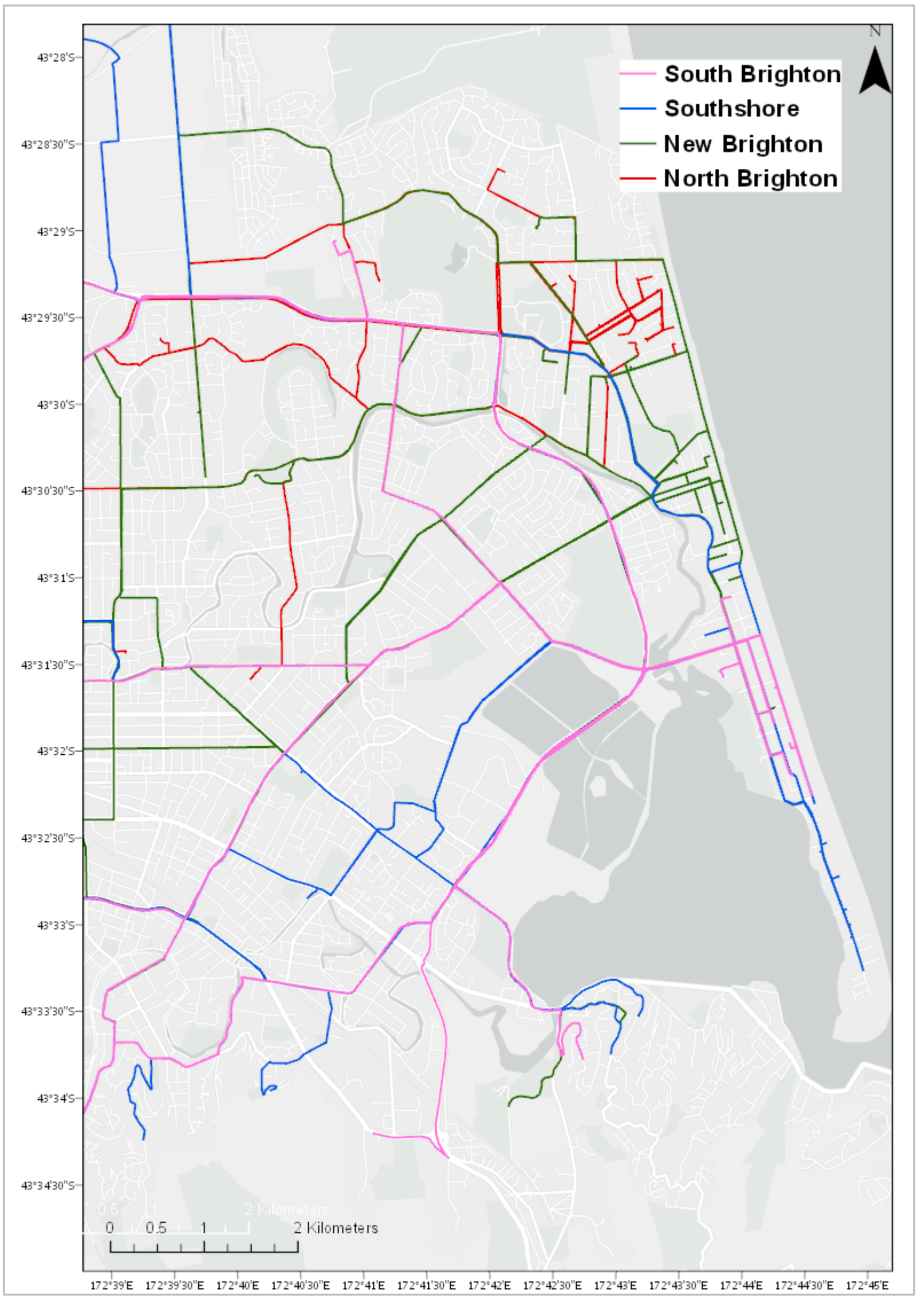

Figure 7.19: Evacuation routes focusing on the Coastal Ward zoomed in to the Brighton Spit.

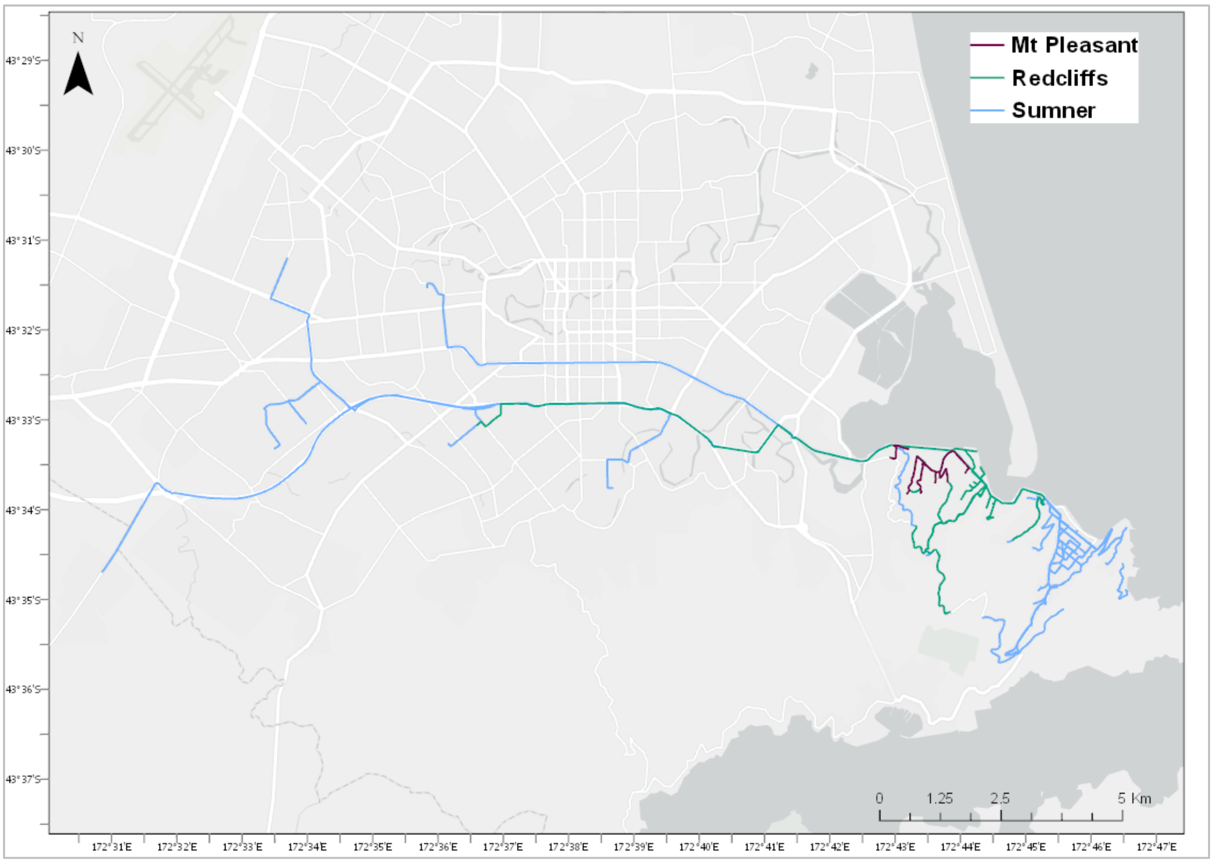

Figure 7.20: Evacuation routes focusing on the Heathcote Ward.

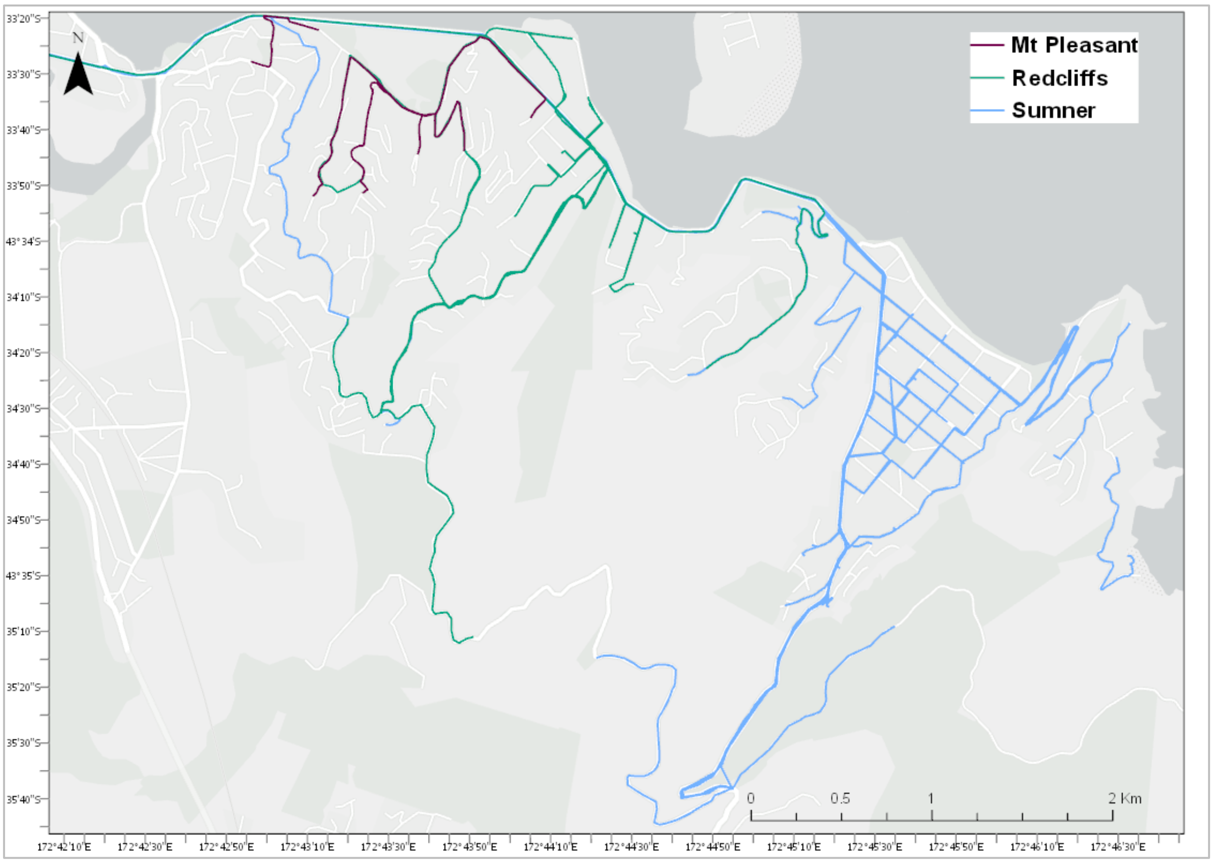

Figure 7.21: Evacuation routes focusing on the Heathcote Ward zoomed in to Sumner, Redcliffs and Mt Pleasant.

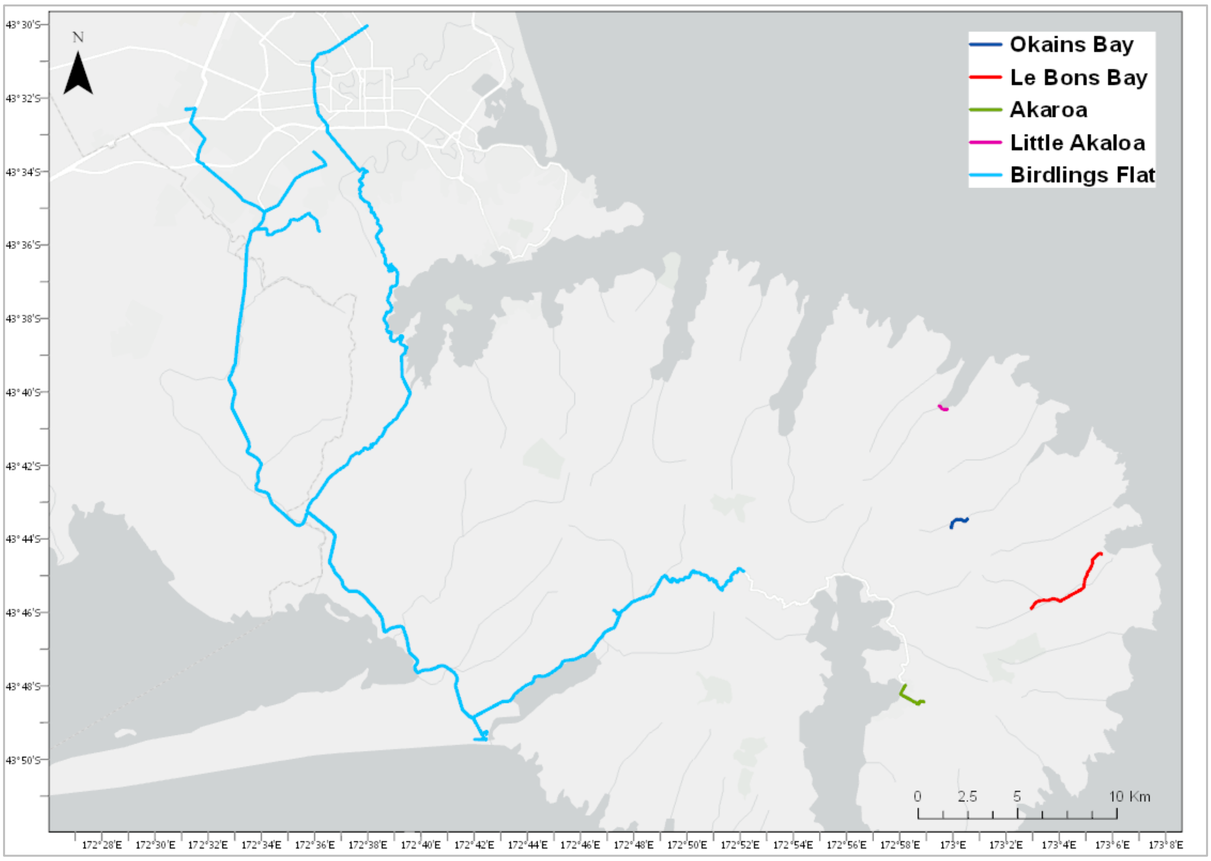

Figure 7.22: *Evacuation routes focusing on the Banks Peninsula Ward.*

Based on the evacuation paths recorded, an evacuation paths heat map was generated (Figure 7.23). This heat map shows the most common routes taken were in New Brighton and North Brighton (especially around the roundabouts of QEII Highway with Travis Road, New Brighton Road, Bridge Street and Breezes Road) and in Sumner, Redcliffs and Mt Pleasant (towards the city centre through Main Road).

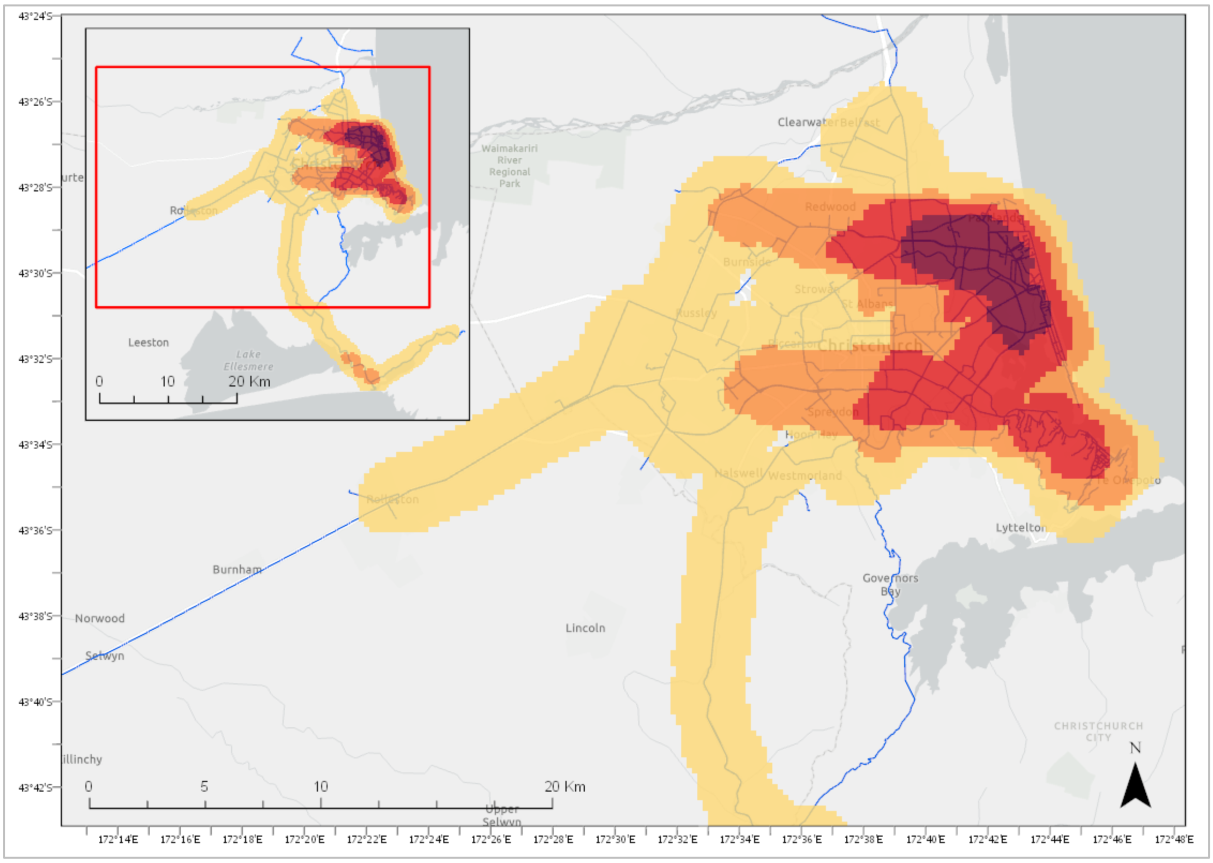

Figure 7.23: Heat map of evacuation routes taken by survey respondents. Lighter orange indicates routes/areas where there were fewer evacuees, while darker reds indicate areas where there were more evacuation routes. The evacuation routes have been included shown by the blue polyline.

h. Issues during Evacuation

i. Assistance to Evacuate

Eight percent (n=1) of respondents from Banks Peninsula and 3% (n=5) from Christchurch required assistance during the evacuation process (Table 7.21). Examples of assistance required during the evacuation process included:

- Banks Peninsula - needing help to carry sick children in the dark to the car (n=1),
- Christchurch – required transportation (n=4),
- Christchurch – a respondent stated that they assisted others in their evacuation by providing transportation (n=1).

Table 7.21: Assistance required for evacuation (n=162)

Were you in need of any assistance for evacuating?	Banks Peninsula	Christchurch
Yes	8% (n=1)	3% (n=5)
No	92% (n=12)	97% (n=144)
Total	100% (n=13)	30% (n=149)

Respondents were then asked about how their need for assistance affected their evacuation process. A further four respondents (one from Banks Peninsula and three from Christchurch) who had not stated that they required assistance in the previous question answered this question. Of the 10 respondents who stated that their need for assistance affected their evacuation process, one respondent from Banks Peninsula (50%) and five from Christchurch (63%) received the assistance they needed so were able to evacuate. An example is one respondent who had no transportation, so walked from New Brighton to Aranui where they were given a ride to the evacuation centre in Linwood. Three people from Christchurch (38%) did not evacuate because of their requirement for assistance (Table 7.22). This was due to a lack of transportation to evacuate and because of caring for frail family members for whom evacuation was difficult.

Table 7.22: Impact of assistance in evacuation process (n=10)

How did your need for assistance affect the evacuation process?	Banks Peninsula	Christchurch
I received the support I needed	50% (n=1)	63% (n=5)
It delayed the evacuation but I evacuated anyway	50% (n=1)	0% (n=0)
It was a barrier so I did not evacuate	0% (n=0)	38% (n=3)
Total	100% (n=2)	100% (n=8)

ii. Congestion

Only 7% (n=1) of respondents from Banks Peninsula and 44% (n=67) of respondents from Christchurch observed congestion either during their travel to their evacuation point, or watching from their evacuation point (Table 7.23). A further five respondents from Christchurch who said they did not observe congestion provided details of congestion. Shown in Table 7.24, this brings the proportion of respondents from Christchurch who observed congestion to 47% (n=72). Congestion was noted by respondents between 12:10 a.m. and 9:00 a.m., but in particular was most frequent around 1:00 a.m. and 2:00 a.m..

Table 7.23: Congestion observed during evacuation (n=167)

Did you observe congestion?	Banks Peninsula	Christchurch
Yes	7% (n=1)	44% (n=67)
No	93% (n=14)	56% (n=85)

Total	100% (n=15)	100% (n=152)

Table 7.24: Revised proportion of respondents from Christchurch who observed congestion (n=152)

Did you observe congestion?	Christchurch
Yes	47% (n=72)
No	53% (n=80)
Total	100% (n=152)

Traffic was estimated by respondents to be moving between 0 and 110km/hr in areas that were congested (Table 7.25).

Table 7.25: Estimated speed of traffic during congestion during evacuation (km/hr).

Speed of Congestion	Banks Peninsula	Christchurch
Minimum	50	0
Maximum	110	70
Average	85	23.46

Shown in Figure 7.24, congestion was observed in Birdlings Flat, Mt Pleasant, New Brighton, North Brighton, Redcliffs, South Brighton, Southshore and Sumner. Roads that were frequently noted as congested included Evans Pass Road (n=8), Wakefield Avenue (n=4), Keyes Road (n=5), Bridge Street (n=14), Pages Road (n=6), Bowhill Road (n=6), Travis Road (n=6) and Estuary Road (n=6).

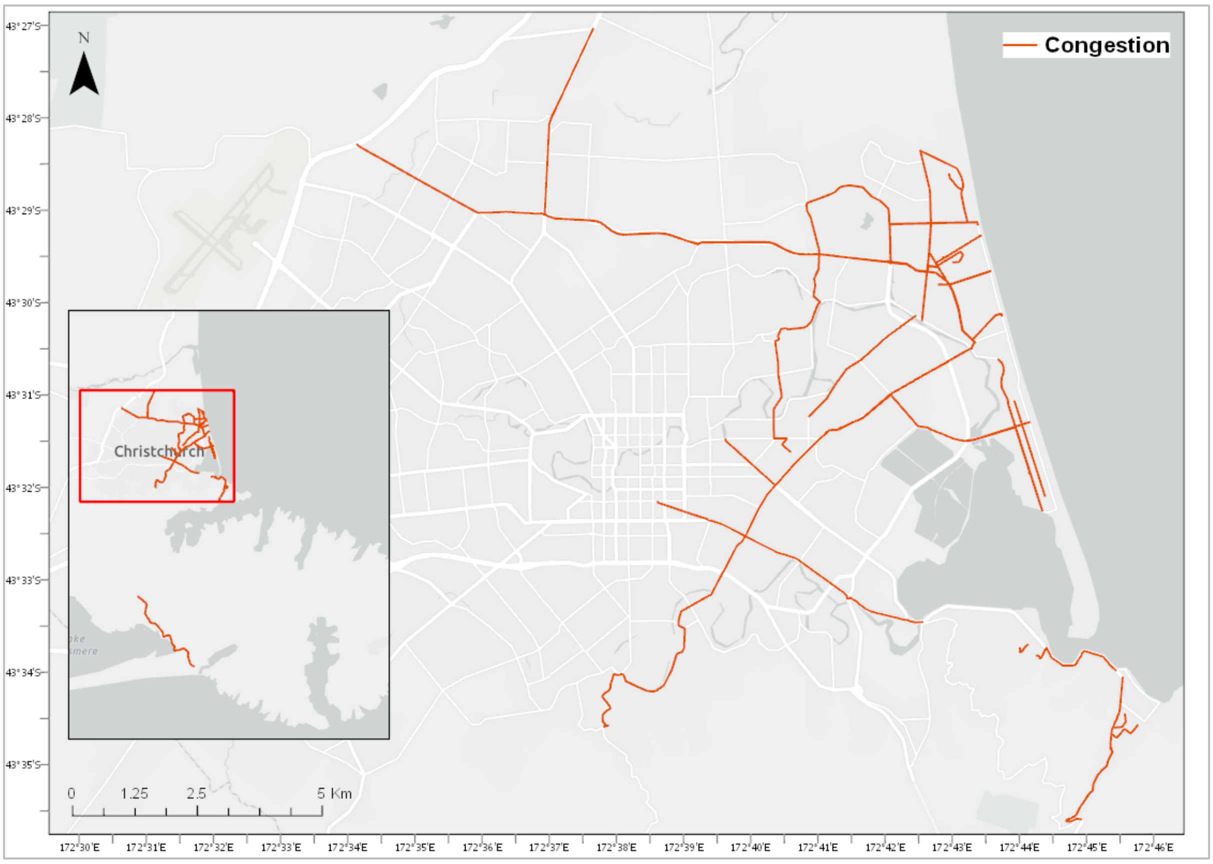

Figure 7.24: Congestion map

Survey respondents were asked to comment on the congestion. The first comment is from a respondent from Banks Peninsula, while the remainder of the comments are from evacuees from Christchurch:

- The main highway heading out of Banks Peninsula had traffic,
- A few cars left straight after the earthquake and were ahead of traffic, but after the sirens were activated there were a lot of people suddenly in cars,
- Within 5 minutes of the sirens going off, traffic could be seen to be backed up at Bridge Street (South Brighton),
- Getting out of driveways was difficult, people walking got further,
- Roads needed to be immediately controlled by police with both sides being used to get people as far away as possible,
- There was a long stream of lights coming up the hill (Sumner) for a few hours,
- The roundabouts in New Brighton, South Brighton and North Brighton were very congested – it took one respondent 20 minutes to get through the Bowhill Road roundabout,
- Fear that the bridge at Pages Road was unsafe to cross created congestion in New Brighton,

- Roads leading from the flats to the hills around Mt Pleasant, Sumner and Redcliffs became congested. This was particularly noted on Evans Pass Road (Sumner) where there was a backlog of traffic, causing evacuees to park and walk the rest of their route.

i. Return from Evacuation Point

Survey respondents who evacuated spent between 0.25 and 16 hours at their evacuation point (Table 7.26). The average time which people evacuated in Banks Peninsula was 5.42 hours, while for Christchurch was 5.98 hours. One respondent from Christchurch reported that they evacuated for 3 days.

Table 7.26: Time spent at evacuation point

How long did you stay at your evacuation point?	Banks Peninsula (n=12)	Christchurch (n=126)
Minimum	1.5 hours	0.25 hours
Maximum	9 hours	16 hours
Average	5.42 hours	5.98 hours

Survey respondents were asked to select all of the reasons that informed their decision to return from their evacuation point.

Shown in Table 7.27, the most common reasons for Banks Peninsula respondents to return from their evacuation point included when the respondents felt it was safe and there was no evidence of danger (53%, n=8), and after a reasonable time (40%, n=6). Other reasons that informed decisions to return home included:

- Watched the tide for unusual movements and did not see any (n=1).

The most common reasons for Christchurch respondents to return from their evacuation point as shown in Table 7.27, included when the respondents felt it was safe and there was no evidence of danger (39%, n=56), and after a reasonable time (41%, n=59). Other reasons that informed respondents' decisions to return home included:

- Needed to get ready for work (n=4),
- The deactivation of the sirens (n=12),
- News of others returning (n=3),
- Emergency services (n=1),
- News of houses being burgled (n=1).

Table 7.27: Reason to return from evacuation point (n=158)

Why did you decide to return from your evacuation point?	Banks Peninsula (n=15)	Christchurch (n=143)
When I felt it was safe (evidence there was no danger)	53% (n=8)	39% (n=56)
After discussing with others	13% (n=2)	22% (n=31)
After a reasonable time	40% (n=6)	16% (n=23)
When I received an official 'All Clear' message	20% (n=3)	41% (n=59)
Other	27% (n=4)	31% (n=44)

j. Other Comments about the Event

Survey respondents were given the opportunity to express any other comments they had about the evacuation. Some of these comments are below.

Banks Peninsula:

- The information from Civil Defence was conflicting and poor.
- Would like advice about best place to evacuate to for Birdlings Flat and Akaroa.
- In Akaroa the evacuation centre is not felt to be high enough.
- There was a breakdown in communication and the police and Civil Defence seemed to have different opinions on the need to evacuate.
- Concern about the lack of a warning system (in Le Bons Bay) where there is no cell phone service, but there are landlines that could be used for a warning system.
- There is no earthquake signage for directions to high points.
- Civil Defence Post in Little River was not open.

Christchurch

- The siren controlled when people evacuated and returned home.
- The delay in activating the siren was an issue as this was the signal people needed to evacuate.
- The use of the tsunami sirens was poor – they were activated late and went on and off at times.
- The sirens sounds are confusing and there were different patterns – it was felt that there needed to be a sound for all clear.
- The sirens stayed on so long considering how close the earthquake was.
- We took longer than we should have to leave because we looked for official announcements.
- Leaving early (before the sirens) allowed people to avoid traffic and congestion.

- Lots of people assumed because the sirens hadn't gone off that there was no need to evacuate and once they went off the roads were so congested that traffic was at standstill or crawling.
- People parked a short way up the hill (in Sumner) and created a backlog for others evacuating.
- There was conflicting information – Civil Defence on radio said to evacuate but the sirens weren’t activated.
- Information on radio, television and the internet was contradictory - no official messages.
- The traffic was moving steadily cross the waterfront with most people travelling over the speed limit.
- Trust in Civil Defence Christchurch and MCDEM (NEMA) decreased after this event.
- People have realised the importance of evacuation plans – some have re-evaluated where they would evacuate to.
- Confusion over the location of evacuation centres – Linwood is considered too far.
- People evacuated too far inland and there was no information on where to go.
- Too many people evacuated that did not need to.
- We are now aware that if you are 1km from the ocean you need to evacuate – we are 1.3km so would not evacuate if there is a tsunami warning.
- I would have liked an explanation on the CCC website about what to do.
- The main concern was the earthquake shaking and not the tsunami threat.
- Maybe opening both sides of the road to evacuate would help decrease traffic – particularly QEII and Travis Road.
- Choke-points in the road need traffic control.
- Roads were unable to cope with the extreme number of cars at the peak of evacuation.
- People avoided traffic by driving on the wrong side of the road.
- There was a backlog of traffic in Sumner (Evans Pass Road) as vehicles evacuated up the hill but only parked a short way up the hill.
- It would be great to have information from GNS on fault lines and threats to coastal areas shared with coastal residents.
- If it was a locally generated tsunami & it did arrive there would have been a lot of casualties/dead – there was no quick way out.
- I wasn’t going to leave because I didn’t have anywhere to go – it is hard to just turn up with children and pets at no notice in middle of night.
- We had no cohesive information and felt in limbo trying to make an informed decision.
- Learnt later if long and strong – evacuate – based on that statement would have left immediately, after the quake stopped.

k. Risk Perception and Preparedness

i. Risk Perception and Preparedness Actions before 2016

Table 7.28 shows respondents knowledge of tsunami hazards and the need to evacuate prior to the 2016 evacuation. Prior to the 2016 Kaikōura earthquake, 60% of respondents from Banks Peninsula reported that they had a good or very good knowledge of tsunami hazards and the need to evacuate (38%, n=73 and 23%, n=44). A total of 16% of respondents from Christchurch felt that their knowledge of tsunami hazards and the need to evacuate was poor or very poor (4%, n=6 and 12%, n=20).

Table 7.28: Tsunami risk knowledge prior to 2016 Kaikōura earthquake (n=190)

Prior to the 2016 Kaikōura earthquake how would you describe your knowledge of tsunami hazards and the need to evacuate?	Banks Peninsula	Christchurch
Non-existent	4% (n=1)	1% (n=2)
Very poor	4% (n=1)	4% (n=6)
Poor	8% (n=2)	12% (n=20)
Fair	24% (n=6)	21% (n=35)
Good	40% (n=10)	38% (n=63)
Very good	20% (n=5)	24% (n=39)
Total	100% (n=25)	100% (n=165)

Respondents were asked to select all of the information sources that they used to inform their evacuation decision (summarised in Table 7.29).

The common information sources used by respondents from Banks Peninsula included media coverage of previous tsunami (67%, n=16) and discussions with friends and family (58%, n=14). Only 4% (n=1) were unaware of tsunami hazards. Other information sources informing 13% (n=3) of respondents with sources including:

- Talking to neighbours and community members (n=1),
- Previous experience with earthquakes and tsunami warnings (n=2).

Respondents from Christchurch reported that media coverage from previous tsunami (59%, n=106) and Civil Defence information (47%, n=84) helped inform their evacuation decision. Three percent (47%, n=84) of respondents were unaware of the need to evacuate. Other information sources were used by 16% (n=29) of respondents and included:

- The 'Long and Strong, Get Gone' campaign (n=2),
- Previous disaster experience including Canterbury Earthquakes (n=2), Samoa Tsunami (n=2) and Thailand Tsunami (n=1),
- Civil Defence information (including from CCC CDEM) (n=5)
- Tsunami siren testing (n=2).

Table 7.29: Information sources to inform evacuation decision (n=204)

What were your information sources to inform you to evacuate?	Banks Peninsula (n=24)	Christchurch (n=180)
I was not aware of tsunami hazards and the need to evacuate	4% (n=1)	3% (n=6)
Civil Defence information	33% (n=8)	47% (n=84)
Formal education - primary/intermediate school	13% (n=3)	10% (n=18)
Formal education - secondary school	25% (n=6)	7% (n=12)
Formal education - tertiary education	8% (n=2)	10% (n=18)
Media coverage of previous tsunami	67% (n=16)	59% (n=106)
Documentaries	42% (n=10)	33% (n=59)
Books or articles	38% (n=9)	34% (n=62)
Public education sessions - Civil Defence	21% (n=5)	27% (n=49)
Public education sessions - other	25% (n=6)	14% (n=25)
Discussions with Civil Defence staff	13% (n=3)	9% (n=16)
Discussions with family/friends	58% (n=14)	44% (n=79)
Other	13% (n=3)	16% (n=29)

Respondents were asked how their knowledge of tsunami influenced their behaviour prior to the 2016 evacuation. Multiple behaviours/actions could be selected. Answers have been summarised below in Table 7.30.

In Banks Peninsula 52% (n=13) of respondents noted that their tsunami knowledge did not influence their behaviour before the 2016 evacuation. Forty-eight percent (n=12) reported that they had discussed an evacuation plan with others. Other behaviours included:

- Preparing an evacuation route over a back fence (n=1).

Prior to the 2016 evacuation, 43% (n=70) of respondents from Christchurch had discussed or prepared their evacuation plan with family or friends. Thirty-five percent (n=56) had prepared an emergency kit. Other behaviours included:

- Evacuate immediately (n=1),
- Created a partial emergency kit (n=2),
- Had a house bus that had all emergency items required (n=1).

Table 7.30: Influence on behaviour from tsunami knowledge before 2016 Kaikōura earthquake (n=187)

How did your prior tsunami knowledge influence your behaviour before the 2016 Kaikōura earthquake?	Banks Peninsula (n=25)	Christchurch (n=162)
I had discussed/prepared an evacuation plan with family/friends	48% (n=12)	43% (n=70)
I had prepared a go-bag	16% (n=4)	31% (n=50)
I had arranged to check on neighbours	4% (n=1)	14% (n=22)
I had prepared an emergency kit	16% (n=4)	35% (n=56)
It did not influence my behaviour	52% (n=13)	33% (n=54)
Other	8% (n=2)	7% (n=12)

ii. Changes in Preparedness following 2016

Sixty-four percent (n=16) of respondents from Banks Peninsula and 74% (n=111) from Christchurch stated that their prior awareness of tsunami hazards influenced their behaviour immediately after the 2016 Kaikōura earthquake (Table 7.31).

Table 7.31: Influence on behaviour from prior awareness of tsunami hazards after 2016 (n=176)

Did your prior awareness of tsunami hazards influence your behaviour immediately after the 2016 Kaikōura earthquake?	Banks Peninsula	Christchurch
Yes	64% (n=16)	74% (n=111)
No	36% (n=9)	26% (n=40)
Total	100% (n=25)	100% (n=151)

Respondents were asked how their prior knowledge of tsunami influenced their behaviour after the 2016 evacuation. Multiple behaviours/actions could be selected.

Fifty-two percent (n=13) of respondents from Banks Peninsula reported that they listen to the radio for further information, while 44% (n=11) monitored official websites for further information (Table 7.32).

Other behaviours included:

- Preparing an evacuation route over a back fence (n=1).

Sixty percent (n=98) of respondents from Christchurch reported in the survey that after the 2016 event they listened to the radio for further information, while 54% (n=88) monitored official websites for further information (Table 7.32). Other behaviours included:

- Evacuate immediately (n=1),
- Created a partial emergency kit (n=2),

- Had a house bus that had all emergency items required (n=1).

Table 7.32: Examples of the influence on behaviour from prior tsunami knowledge after 2016 (n=189)

How did your prior tsunami knowledge influence your behaviour immediately after the 2016 Kaikōura earthquake?	Banks Peninsula (n=25)	Christchurch (n=180)
It did not influence my behaviour	20% (n=5)	13% (n=21)
Moved to higher ground	32% (n=8)	34% (n=55)
Moved inland/away from beach	28% (n=7)	37% (n=60)
Gathered essential items before evacuating	8% (n=2)	35% (n=58)
Alerted or checked on family/friends/neighbours	16% (n=4)	45% (n=73)
Listened to radio for further information	52% (n=13)	60% (n=98)
Monitored official websites for further information	44% (n=11)	54% (n=88)
Monitored social media for further information	12% (n=3)	35% (n=57)
Other	8% (n=2)	9% (n=15)

Shown in Table 7.33, following the 2016 Kaikōura earthquake, a total of 76% of Banks Peninsula respondents now feel that their knowledge of tsunami hazards and the need to evacuate is good or very good (52%, n=13 and 24%, n=6), while 83% of Christchurch respondents feel that their knowledge is now good or very good (44%, n=73, 39%, n=64).

Table 7.33: Tsunami risk knowledge following 2016 (n=190)

Knowledge of Tsunami Hazards and Need to Evacuate After to 2016	Banks Peninsula (n=15)	Christchurch (n=143)
Non-existent	0% (n=0)	1% (n=2)
Very Poor	4% (n=1)	0% (n=0)
Poor	0% (n=0)	4% (n=7)
Fair	20% (n=5)	12% (n=19)
Good	52% (n=13)	44% (n=73)
Very Good	24% (n=6)	39% (n=64)
Total	100% (n=25)	100% (n=165)

Respondents were asked to select all of the actions they have completed to improve their preparedness towards future earthquake tsunami evacuation events. Answers have been summarised below (Table 7.34).

Following the Kaikōura Earthquake, the most common preparations made by respondents from Banks Peninsula include identifying evacuation routes and destinations (44%, n=11) and discussing an evacuation plan with household and family members (44%, n=11). Other preparations made included:

- Searched online for information specific to Banks Peninsula (respondent noted no information was available) (n=1),
- Put a 'Long and Strong' sign up in shop window (Okains Bay) (1),
- Knowledge to evacuate up the hill (n=1).

Common preparations made by survey respondents from Christchurch included discussing an evacuation plan with family and household members (54%, n=89), identifying evacuation routes and destinations (48%, n=80) and preparing emergency kits (48%, n=79). Other preparations included:

- Improved links with CDEM (1),
- Prepared emergency kits for pets (3),
- Created go-bags that are stored inland at families houses (1),
- Prepare lifejackets, flares, radio, ropes (2).

Table 7.34: Preparations made for future earthquake and tsunami evacuation events (n=190)

Which of the following preparations have you made in case of another significant earthquake and tsunami evacuation?	Banks Peninsula (n=25)	Christchurch (n=165)
I have made no preparations	16% (n=4)	12% (n=20)
Discussed evacuation plan with family/household members	44% (n=11)	54% (n=89)
Arranged to check on neighbours to ensure they are aware of evacuation	16% (n=4)	27% (n=45)
Prepared a go-bag containing essential items	28% (n=7)	41% (n=67)
Identified evacuation routes/destinations	44% (n=11)	48% (n=80)
Made myself aware of evacuation zone information	4% (n=1)	26% (n=43)
Ensured easy access to online information websites	12% (n=3)	22% (n=37)
Prepared an emergency kit with essential supplies	20% (n=5)	48% (n=79)
Other	20% (n=5)	15% (n=25)

Appendix E. Modified Mercalli Intensity Scale

This section explains the Modified Mercalli intensity (MMI) scale that represents earthquake shaking.

MMI	INTENSITY	DESCRIPTION
1	unnoticeable	Barely sensed only by a very few people.
2	unnoticeable	Felt only by a few people at rest in houses or on upper floors.
3	weak	Felt indoors as a light vibration. Hanging objects may swing slightly.
4	light	Generally noticed indoors, but not outside, as a moderate vibration or jolt. Light sleepers may be awakened. Walls may creak, and glassware, crockery, doors or windows rattle.
5	moderate	Generally felt outside and by almost everyone indoors. Most sleepers are awakened and a few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.
6	strong	Felt by all. People and animals are alarmed, and many run outside. Walking steadily is difficult. Furniture and appliances may move on smooth surfaces, and objects fall from walls and shelves. Glassware and crockery break. Slight non-structural damage to buildings may occur.
7	severe	General alarm. People experience difficulty standing. Furniture and appliances are shifted. Substantial damage to fragile or unsecured objects. A few weak buildings are damaged.
8	extreme	Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.
9	extreme	Some buildings are damaged and many weak buildings are destroyed.
10	extreme	Many buildings are damaged and most weak buildings are destroyed.
11	extreme	Most buildings are damaged and many buildings are destroyed.
12	extreme	All buildings are damaged and most buildings are destroyed.

Figure 7.25 MMI shaking intensity and descriptions.

For the purpose of this research, the MMI values were converted into the qualitative shaking intensities:

- MMI 1 -2 = did not feel earthquake;
- MMI 3 = gentle;
- MMI 4 = a jolt or mild;
- MMI 5 = moderate;
- MMI 6-7 = strong/powerful;
- MMI 8-12 = violent/severe.

Appendix F. EVACUATION MODELLING BUILDING INVENTORY

This section presents the building inventories that were created for the areas of Banks Peninsula where evacuation modelling was to be simulated. At the end of this section is a table that has details on the number of rooms in each of the commercial accommodation points within the tsunami evacuation zone in Banks Peninsula. The results of this section (building inventory and commercial accommodation room numbers) were used to inform the number and location of evacuees.

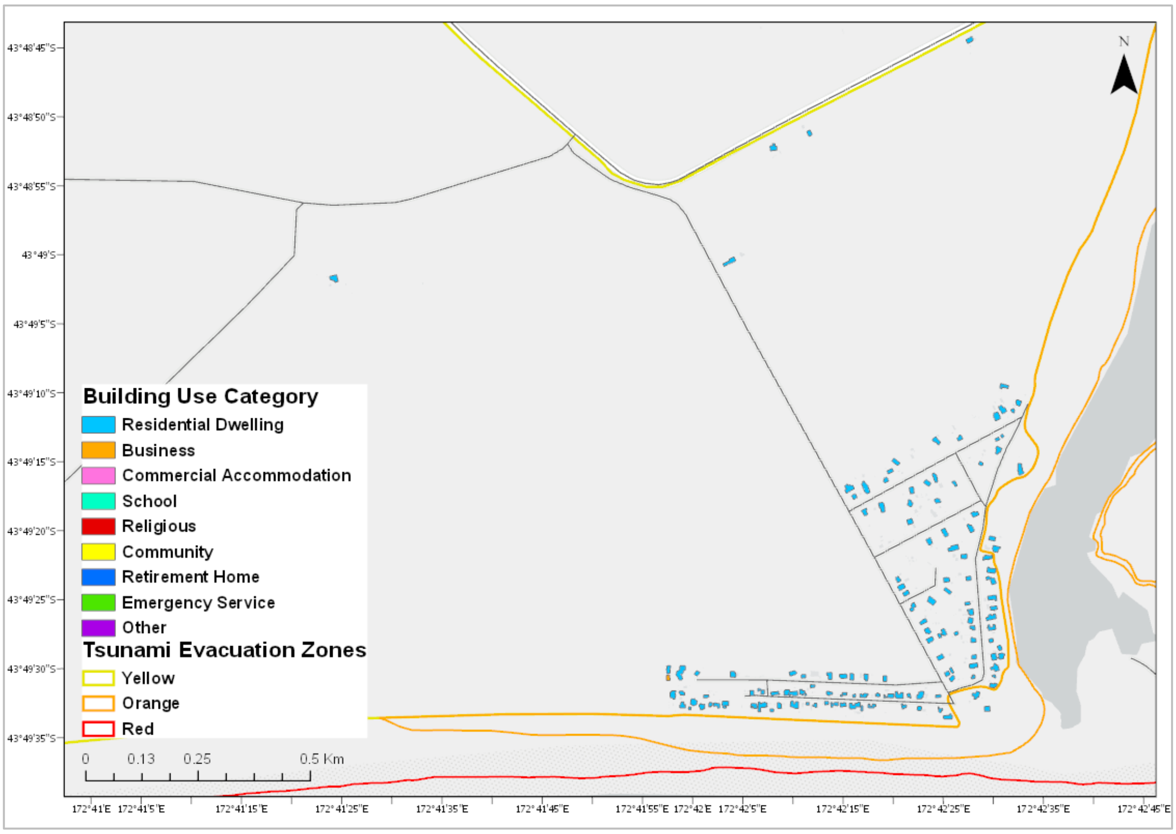

Figure 7.26: Building inventory for buildings within the tsunami evacuation zone in Birdlings Flat.

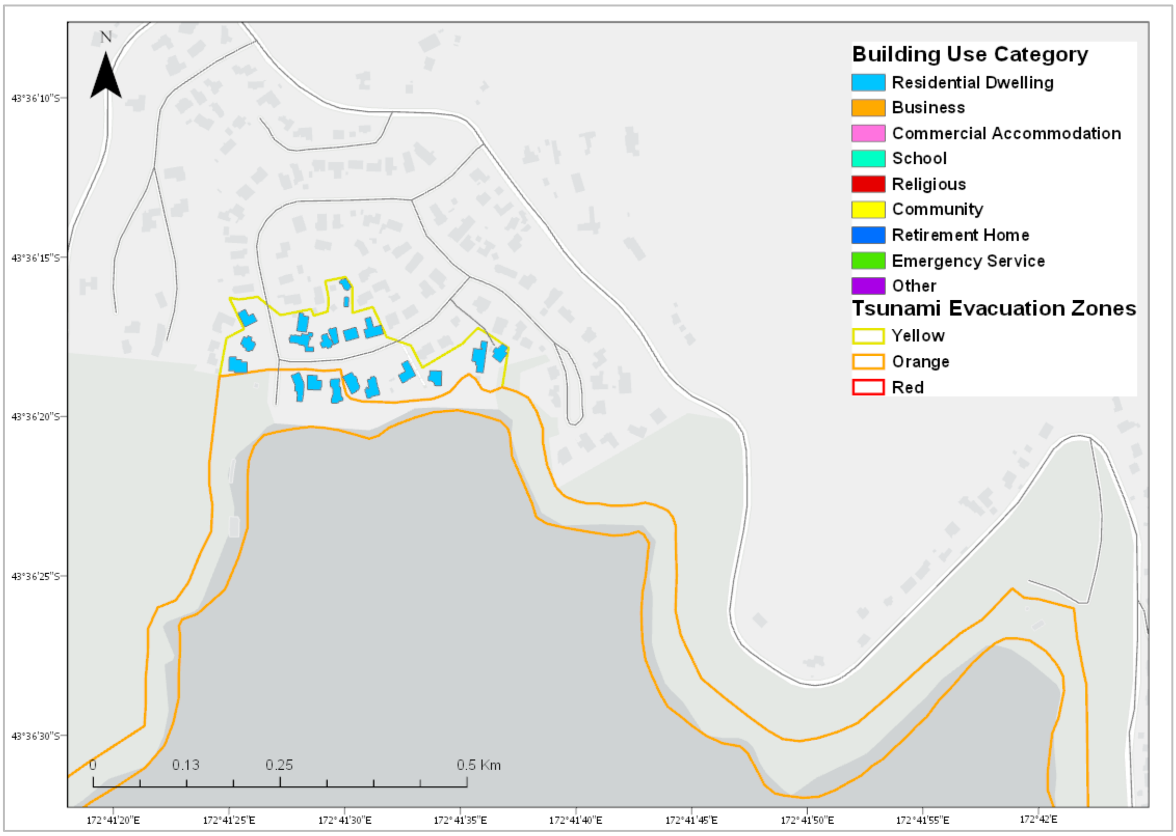

Figure 7.27: Building inventory for buildings within the tsunami evacuation zone in Cass Bay and Corsair Bay.

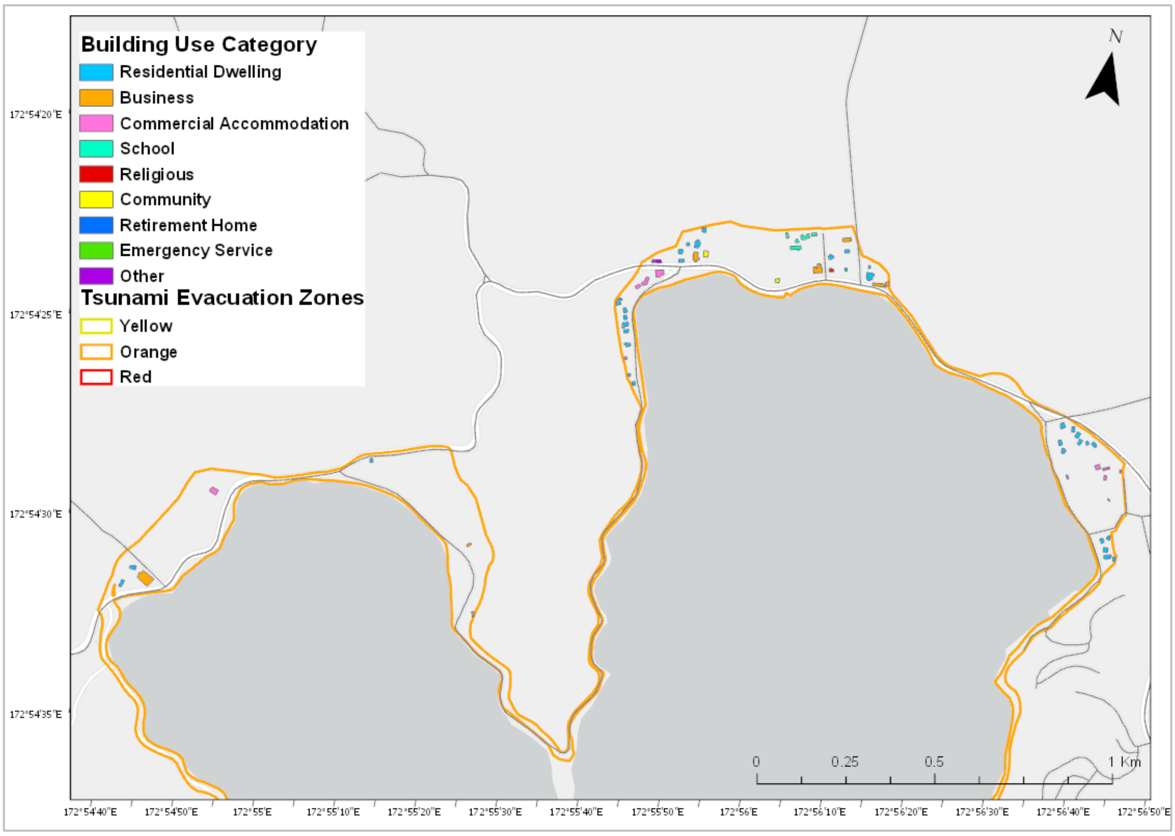

Figure 7.28: Building inventory for buildings within the tsunami evacuation zone in Duvauchelle.

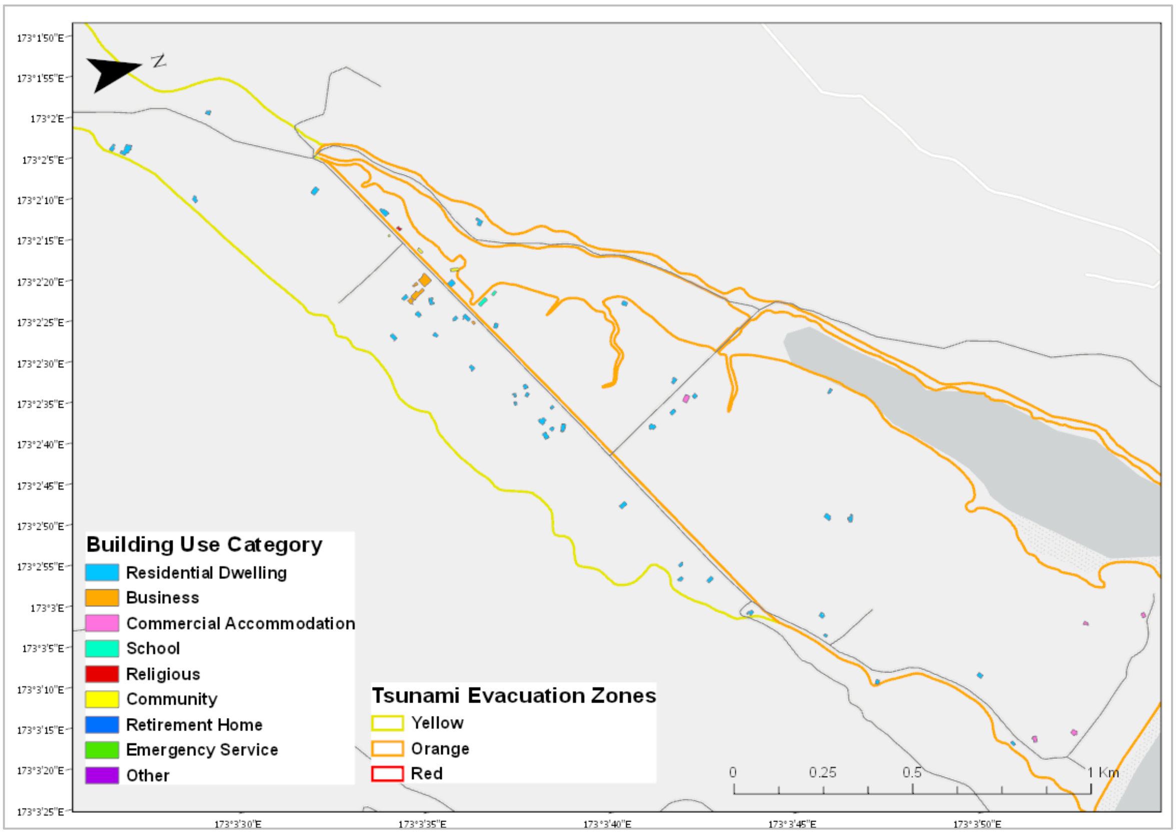

Figure 7.29: Building inventory for buildings within the tsunami evacuation zone in Okains Bay.

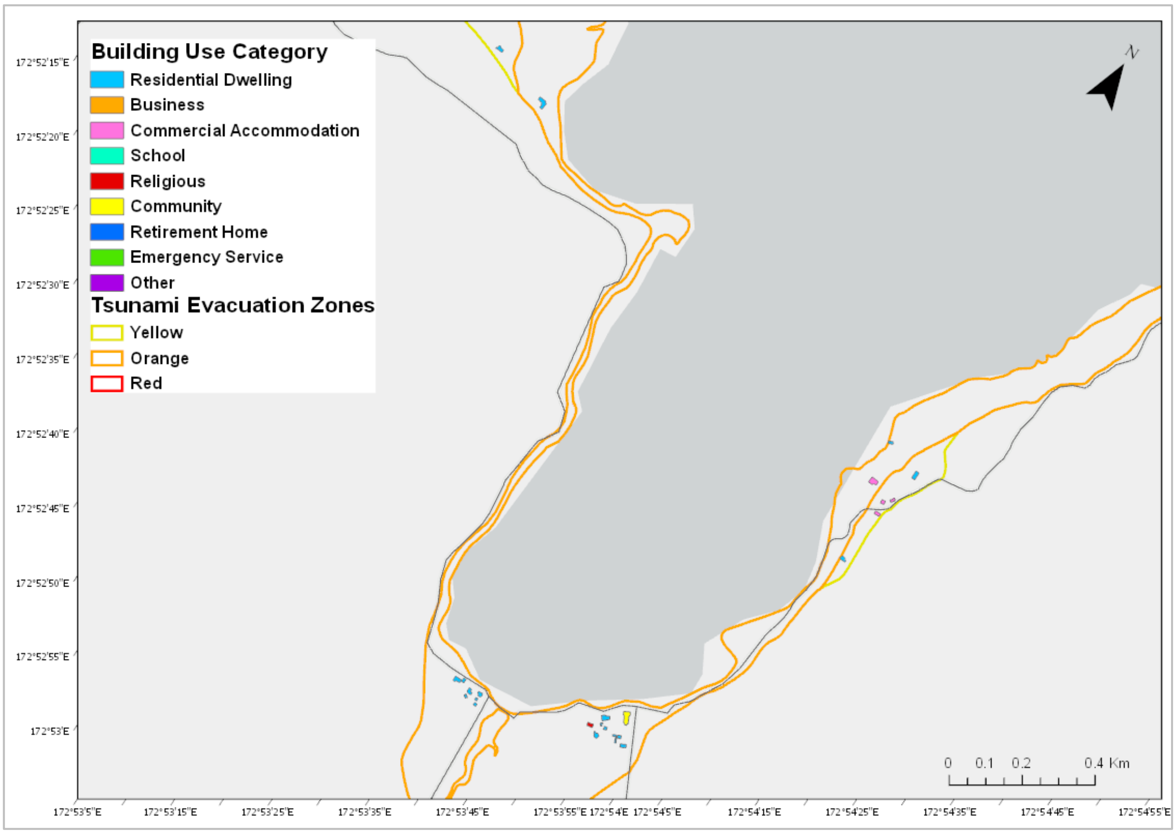

Figure 7.30: Building inventory for buildings within the tsunami evacuation zone in Pigeon Bay.

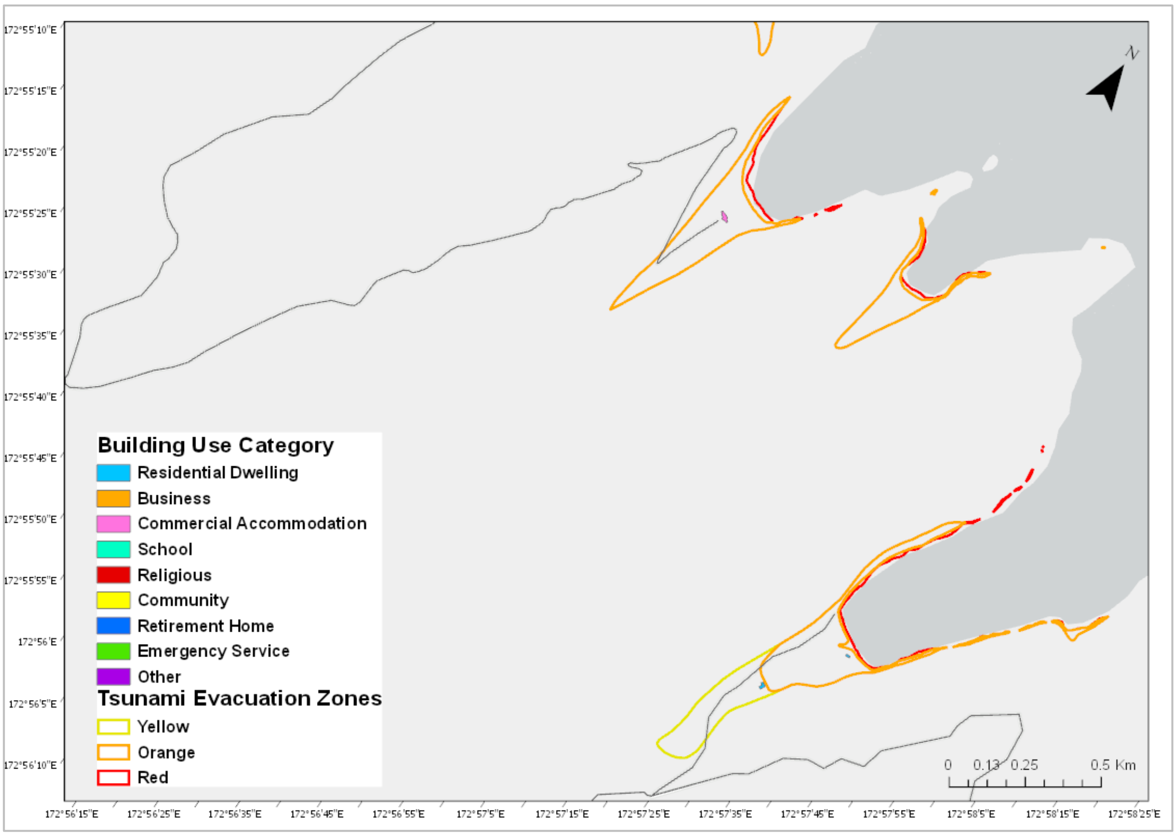

Figure 7.31: Building inventory for buildings within the tsunami evacuation zone in Scrubby Bay and Menzies Bay (included in the Pigeon Bay modelling.

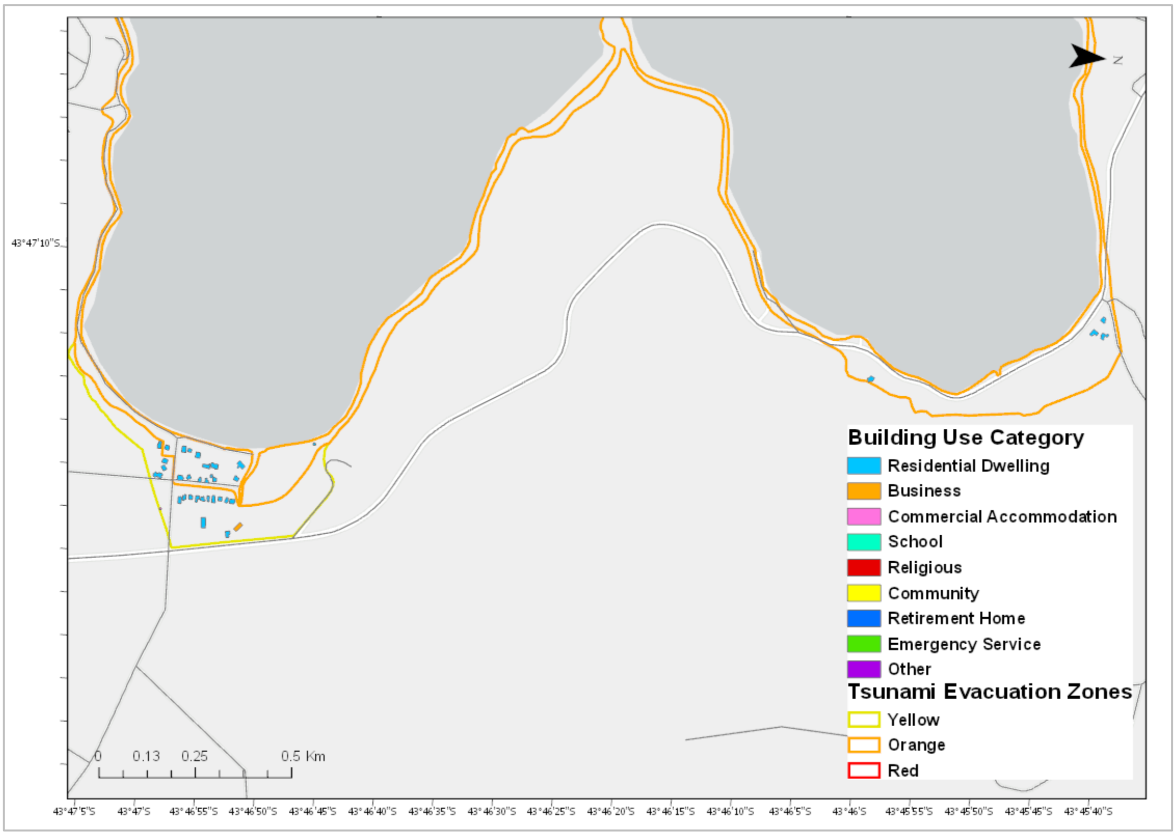

Figure 7.32: Building inventory for buildings within the tsunami evacuation zone in Robinsons Bay and Takamatua Bay.

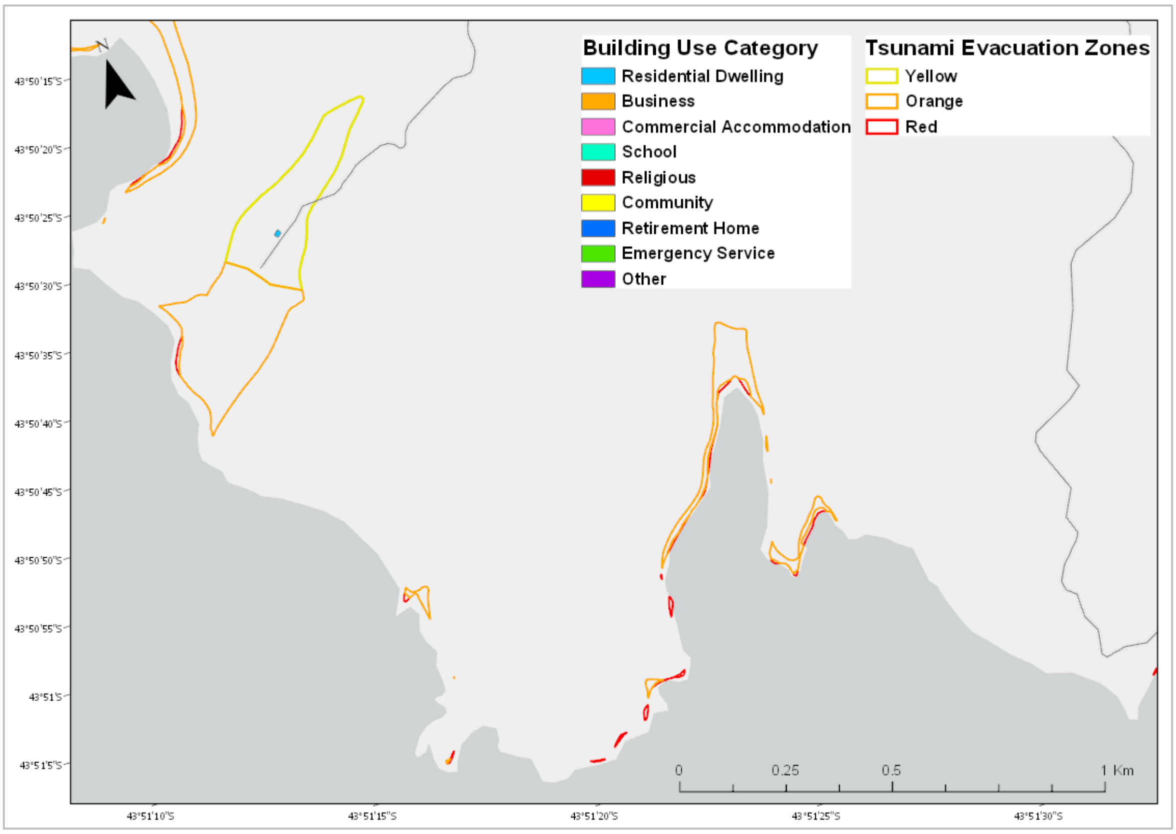

Figure 7.33: Building inventory for buildings within the tsunami evacuation zone in Magnet Bay.

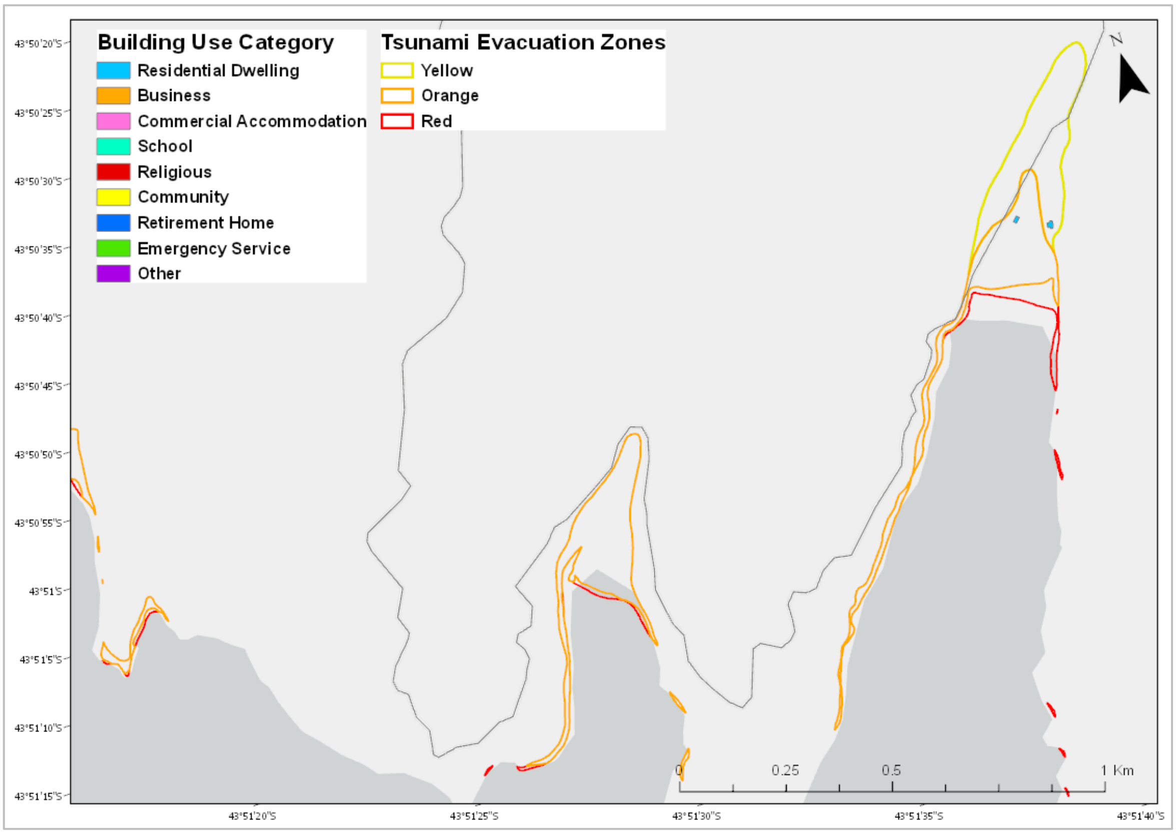

Figure 7.34: Building inventory for buildings within the tsunami evacuation zone in Tumbledown Bay and Te Oka Bay.

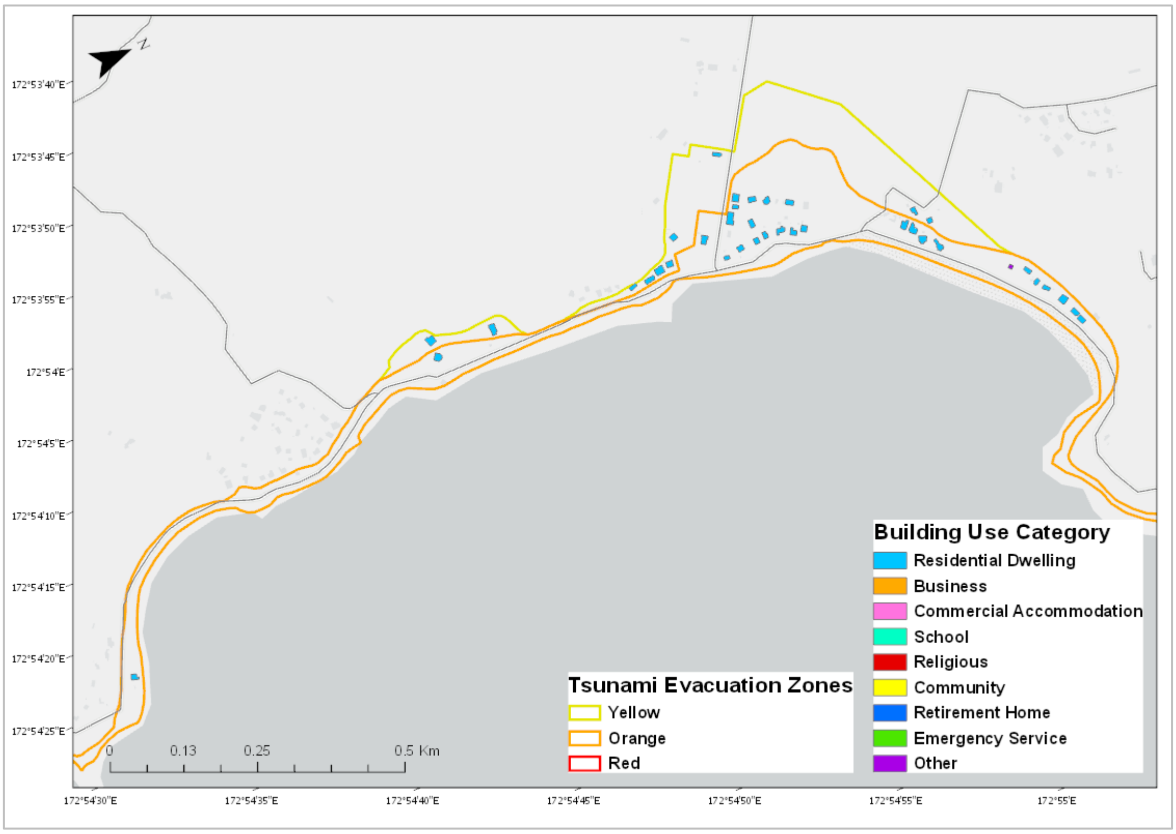

Figure 7.35: Building inventory for buildings within the tsunami evacuation zone in Wainui.

Table 7.35: Number of rooms in commercial accommodation businesses in tsunami evacuation zone in Banks Peninsula. Details could not be found for five accommodation businesses (where N/A is listed for the website). The average number of known rooms for the other businesses informed the number of rooms assigned to these businesses.

Suburb/Location	Accommodation name	Number of Rooms	Website with number of rooms
Akaroa	Akaroa Waterfront Motels	24	https://www.akaroawaterfront.co.nz/accommodation-akaroa.html
Akaroa	Tresori Motor Lodge	12	http://tresori.co.nz
Akaroa	Akaroa on the Beach	3	https://www.akaroaonthebeach.com
Akaroa	La Rochelle Motel	8	http://www.larochellemotel.co.nz/accommodation/
Akaroa	Oinako	6	http://www.oinako.co.nz/akaroa-accommodation-randr.htm
Akaroa	French Bay House	4	https://www.frenchbayhouse.co.nz/room-details
Akaroa	Akaroa Criterion	12	https://www.holidayakaroa.com
Akaroa	A La Villa	4	https://www.akaroa.com/members/a-la-villa/
Akaroa	Maison des Fleurs	1	https://www.holidayhouses.co.nz/listing/15136
Akaroa	Bon Accord	1	https://www.tripadvisor.co.nz/Hotel_Review-g285727-d585547-Reviews-Bon_Accord-Akaroa_Canterbury_Region_South_Island.html
Akaroa	The Grand Hotel	9	https://grandhotelakaroa.co.nz/accommodation
Akaroa	Chez La Mer Backpackers	12	https://www.booking.com/hotel/nz/chez-la-mer-backpackers.en-gb.html?aid=356980;label=gog235jc-1DCAsorgFCF2NoZXotbGEtbWVyLWJhY2twYWNrZXJzSDNYA2iuAYgBAZgBCbgBB8gBDdgBA-gBAYgCAagCA7gC9cXa9AXAAgE;sid=e8ba24b21e6bf22c8ef39aabba96f5d8;dis

			t=0&keep_landing=1&sb_price_type=total&type=total&
Takamatua	L'Abri	3	https://labri.co.nz/akaroa-bed-and-breakfast-labri/
Okains Bay	Opara River Retreat	4	https://opararriverretreat.com/retreat/
Barry's Bay (in Duvauchelle mapping)	Halfmoon Cottage	5	https://www.halfmoon.co.nz/en/
Pigeon Bay	The Stables	2	https://www.annandale.com/accommodations/the-stables
Pigeon Bay	Scrubby Bay	4	https://www.annandale.com/accommodations/scrubby-bay
Akaroa	Maderia Hotel	Unknown	N/A
Akaroa	Les Troupes	Unknown	N/A
Duvauchelle	Duvauchelle Seaside	Unknown	N/A
Duvauchelle	Duvauchelle Motel	Unknown	N/A
Duvauchelle	Duvauchelle B&B	Unknown	N/A

Appendix G. Evacuation Modelling Inputs

This section presents the inputs for the evacuation modelling. This includes figures that feature the safe zones, accommodation, residential and car points, the roading network and the tsunami evacuation zones for reference. At the end of this section is a table that features a breakdown of the number of points input for each category (residential, accommodation, and car points).

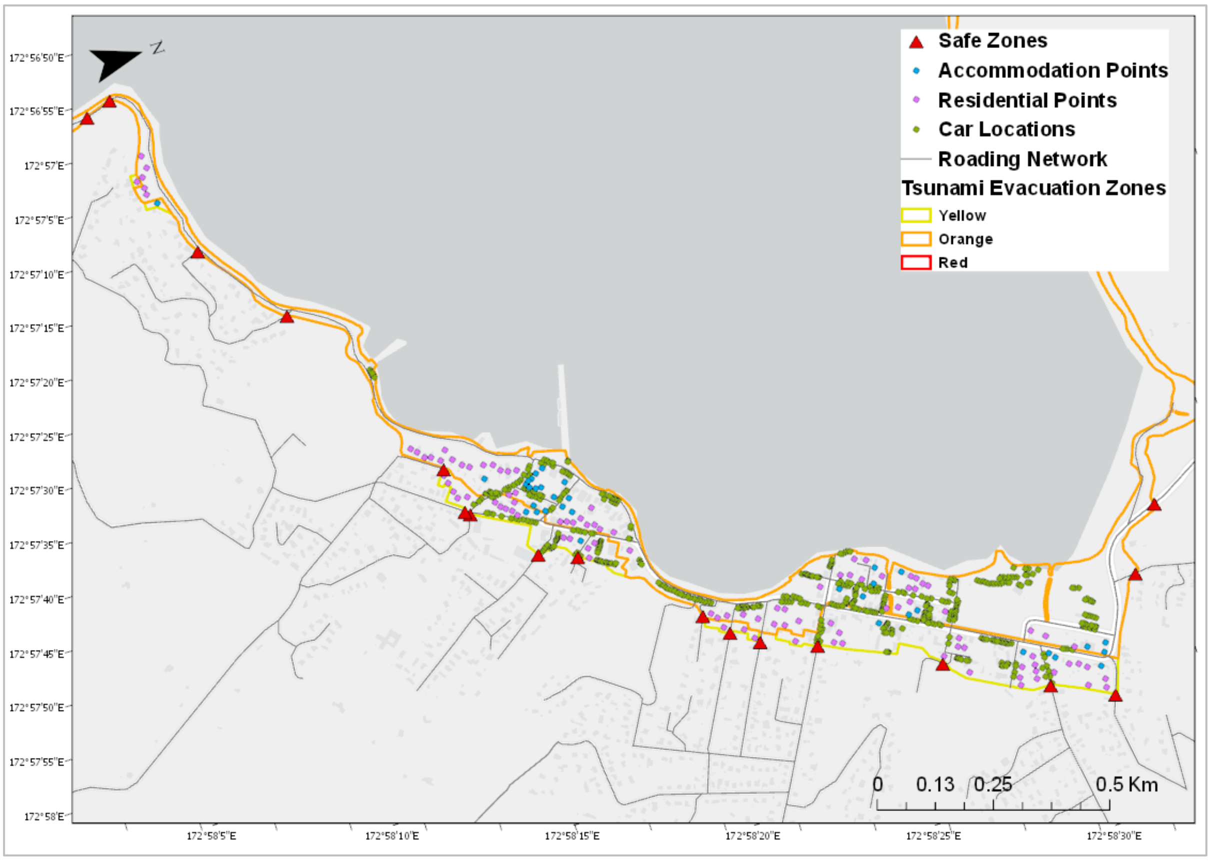

Figure 7.36: Origin points and safe zones that were used to inform the evacuation modelling for Akaroa.

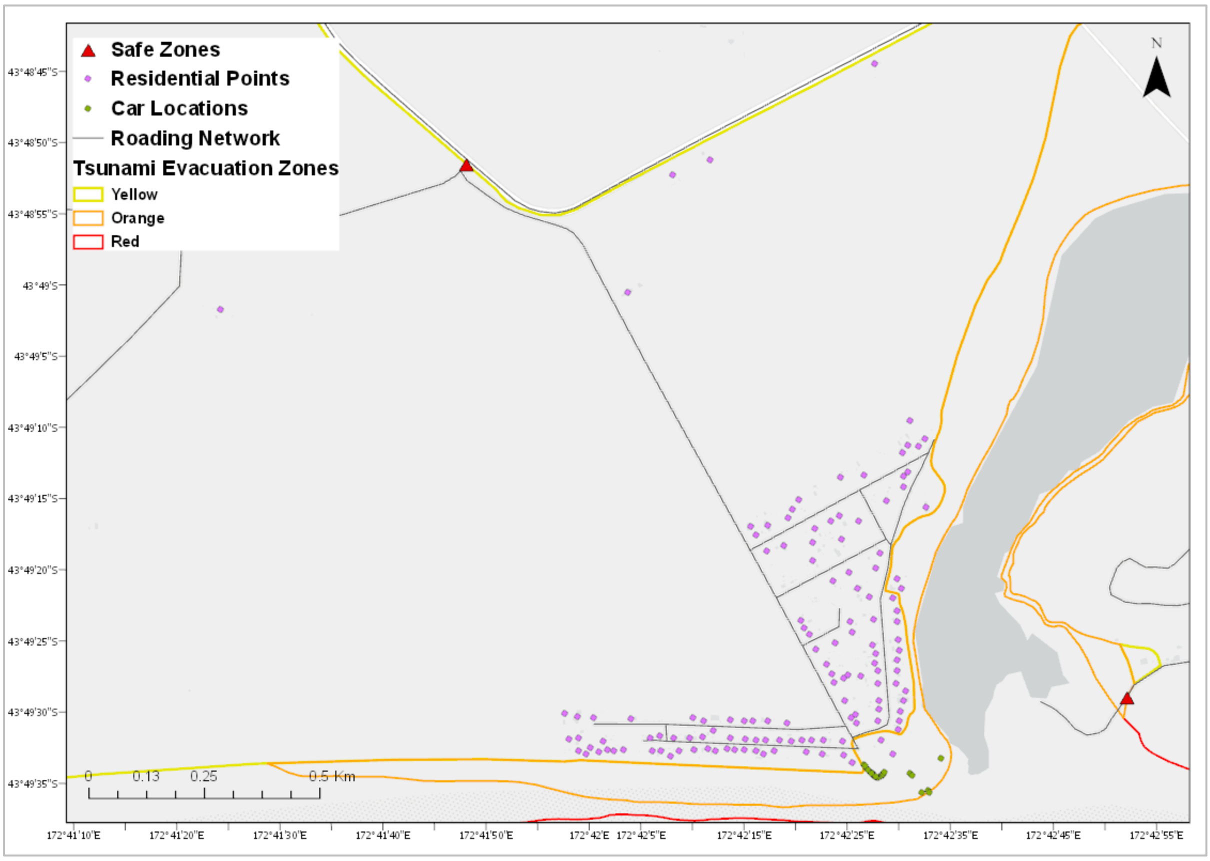

Figure 7.37: Origin points and safe zones that were used to inform the evacuation modelling for Birdlings Flat.

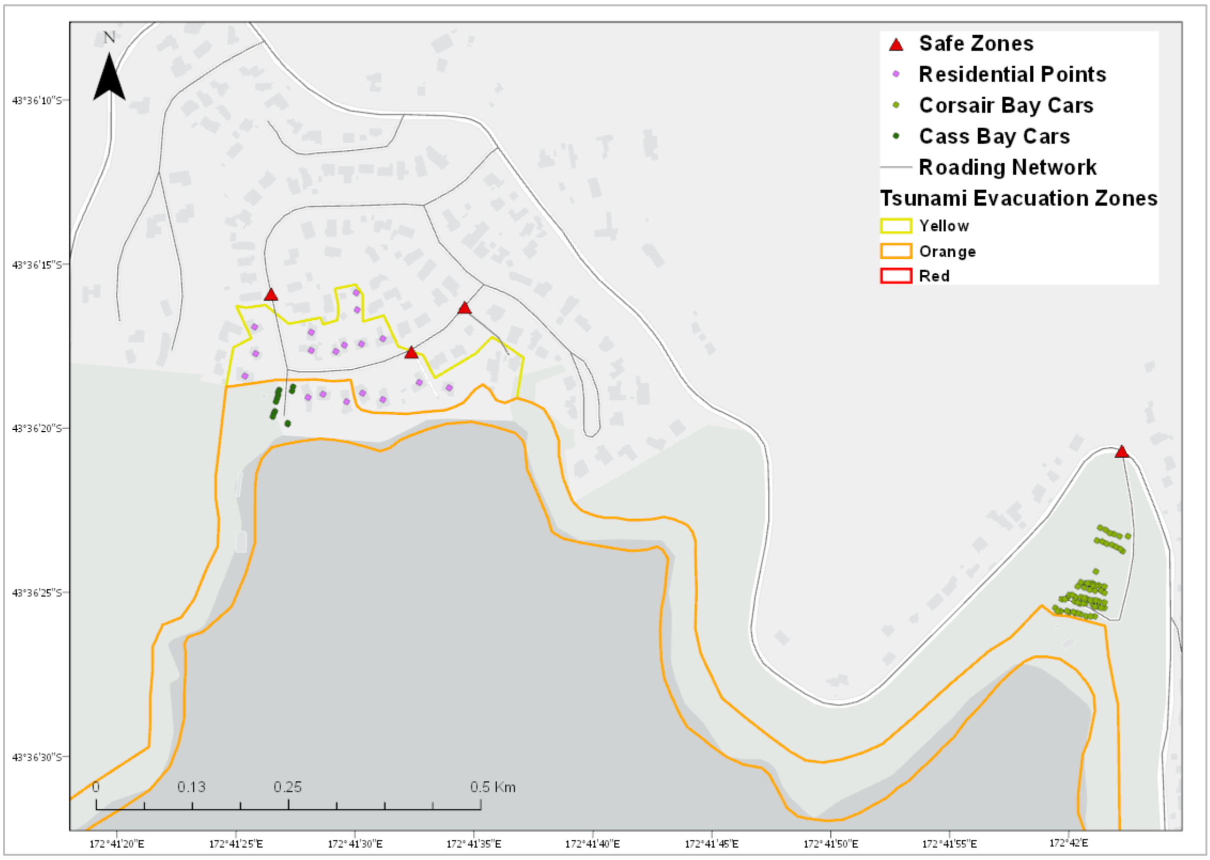

Figure 7.38: Origin points and safe zones that were used to inform the evacuation modelling for Cass Bay and Corsair Bay.

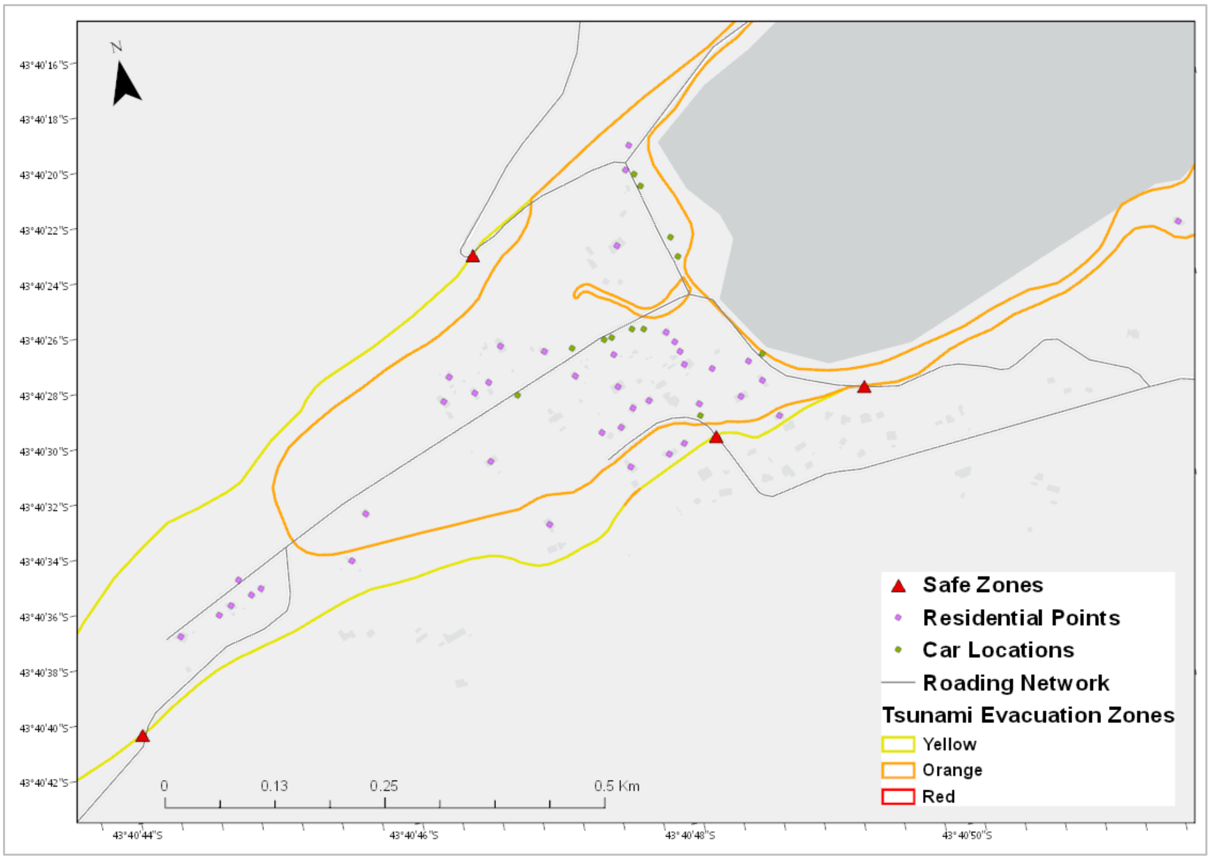

Figure 7.39: Origin points and safe zones that were used to inform the evacuation modelling for Little Akaloa.

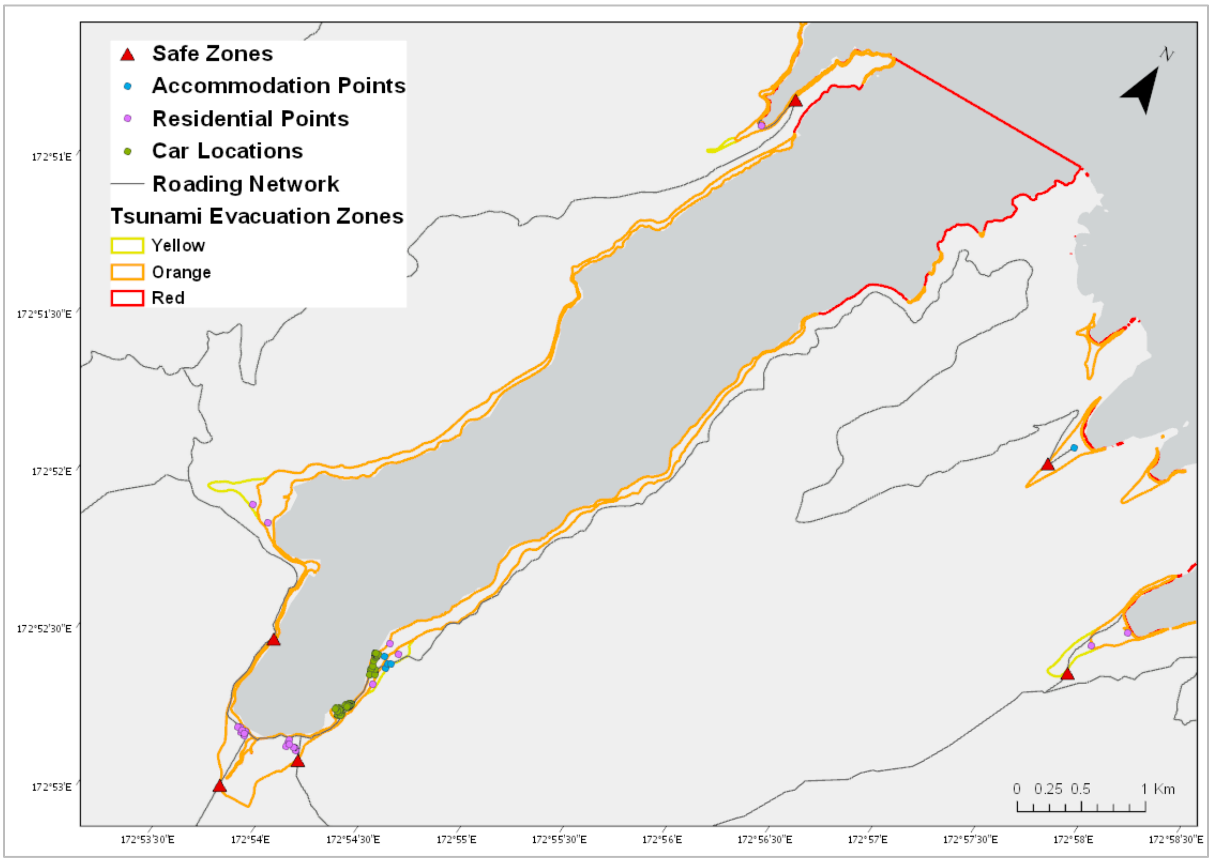

Figure 7.40: Origin points and safe zones that were used to inform the evacuation modelling for Pigeon Bay.

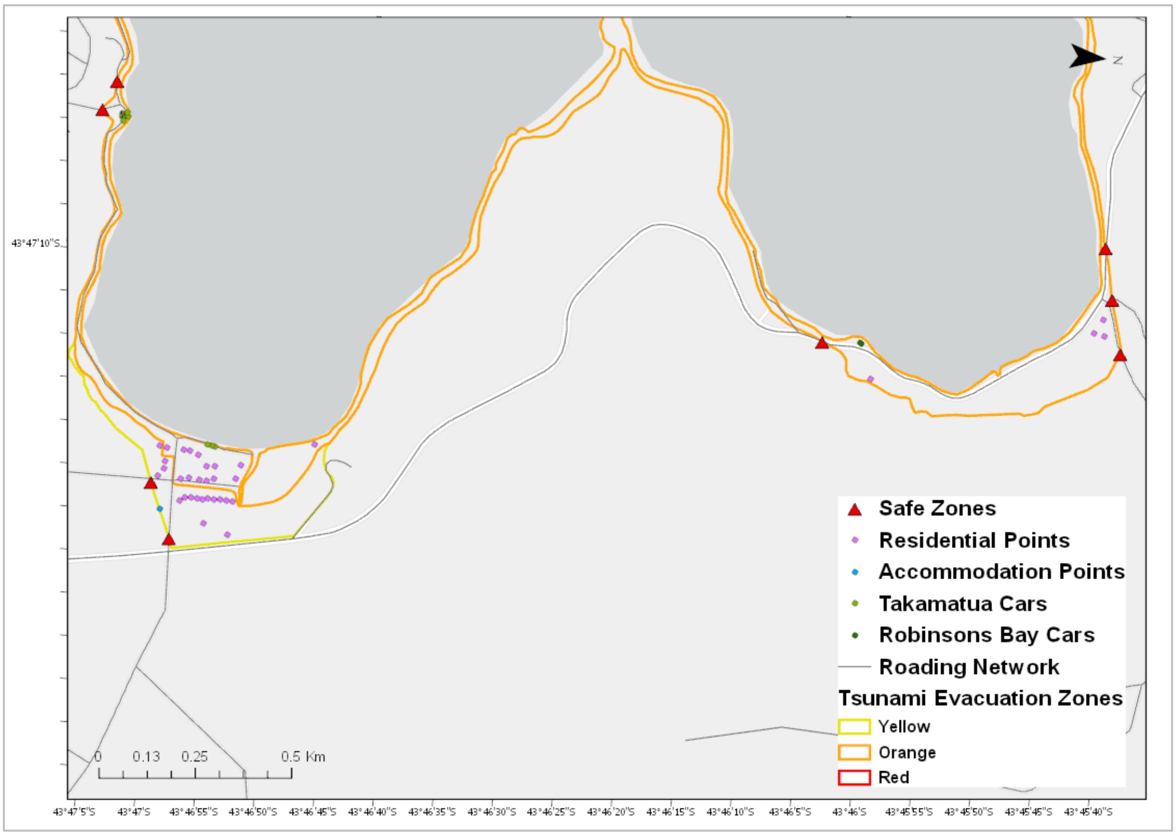

Figure 7.41: Origin points and safe zones that were used to inform the evacuation modelling for Robinsons Bay and Takamatua Bay.

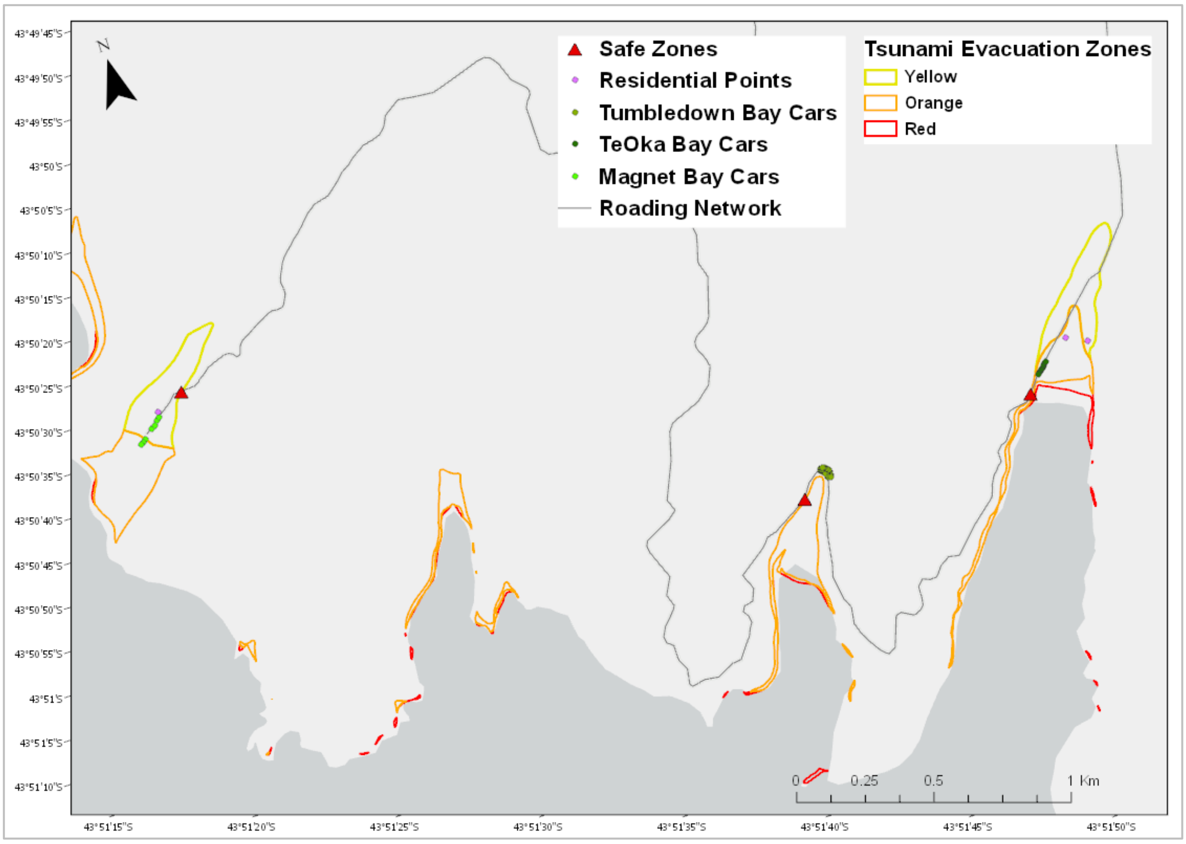

Figure 7.42: Origin points and safe zones that were used to inform the evacuation modelling for Magnet Bay, Tumbledown Bay and Te Oka Bay.

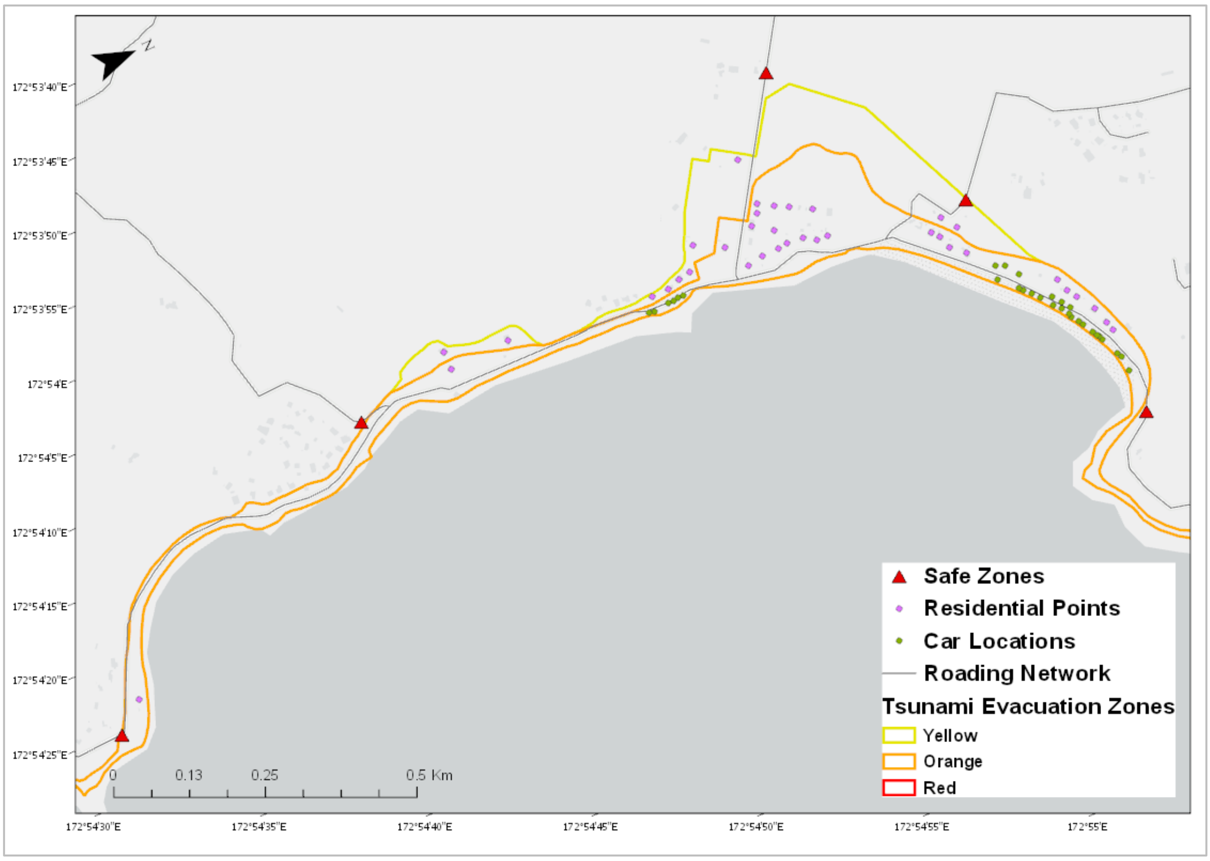

Figure 7.43: Origin points and safe zones that were used to inform the evacuation modelling for Wainui.

Table 7.36: Breakdown of the number of residential, accommodation and observed cars for each area where evacuation modelling was completed.

Location	Number of Points		
	Residential	**Accommodation**	**Cars**
Akaroa	105	39 points (168 evacuees)	460
Birdings Flat	130	0	26
Cass Bay and Corsair Bay	20	0	77
Dauvachelle	34	12 points (36 evacuees)	100 (all camp ground)
Little Akaloa	46	0	12
Okains Bay	22	5 points (8 evacuees)	120 (all camp ground)
Pigeon Bay	44	5 points (6 evacuees)	50 (29 campground, 21 other)
Takamatua Bay and Robinsons Bay	34	1 point (3 evacuees)	15
Te Oka Bay and Tumbledown Bay and Magnet Bay	3	0	76
Wainui	37	0	30

Appendix H. EVACUATION MODELLING RESULTS

This section presents the results of the evacuation modelling. The results follow the same order as the main thesis. At the end of this section figures displaying issues with the evacuation modelling inputs are presented.

a. Akaroa

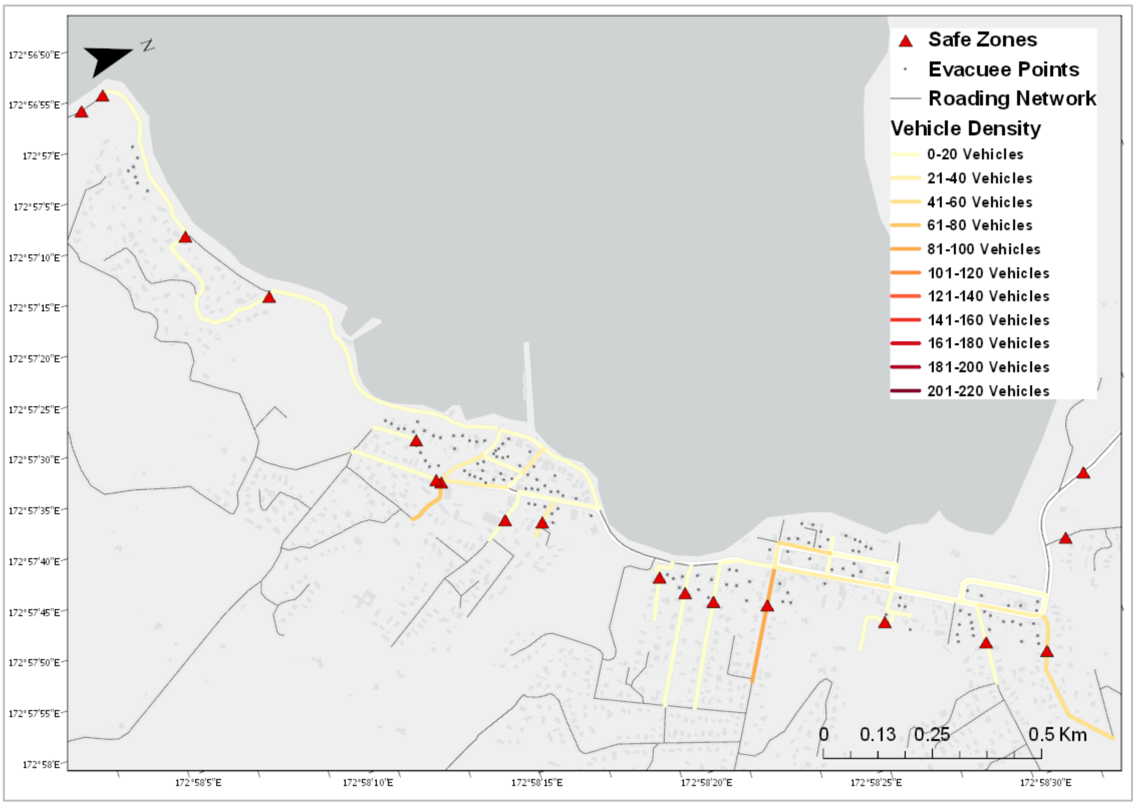

Figure 7.44: Vehicle density count results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

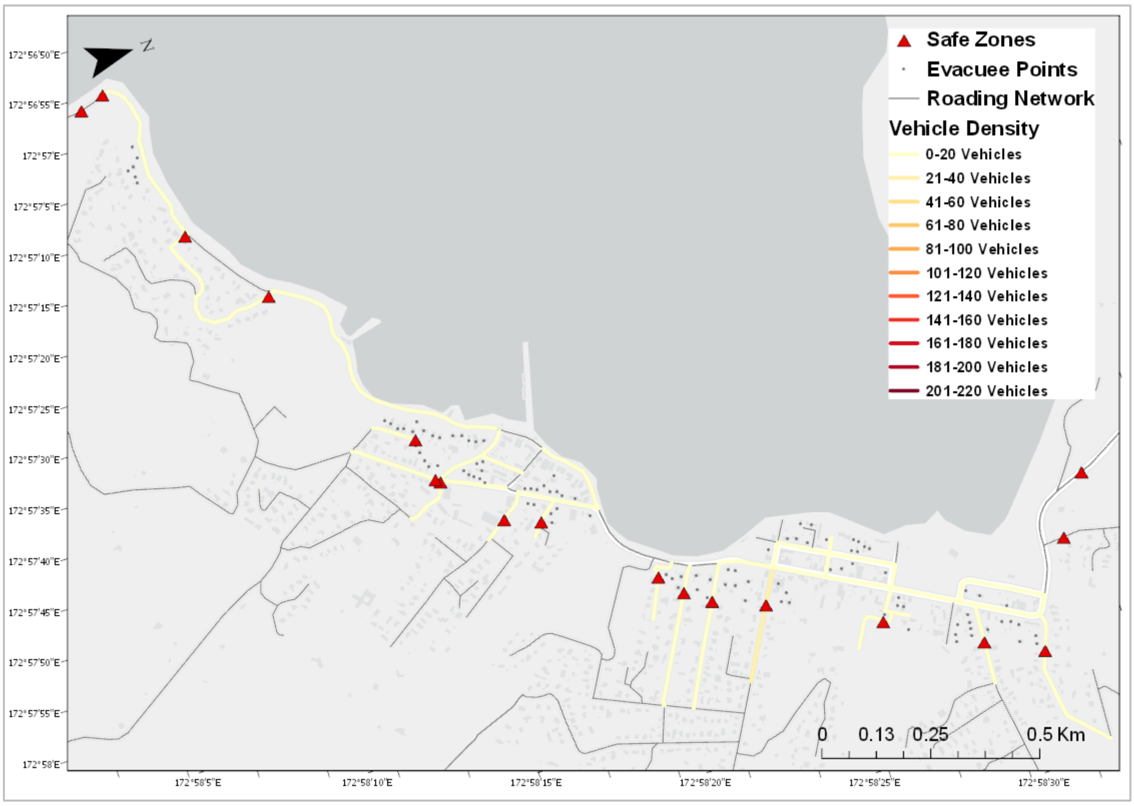

Figure 7.45: Vehicle density count results for Akaroa – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

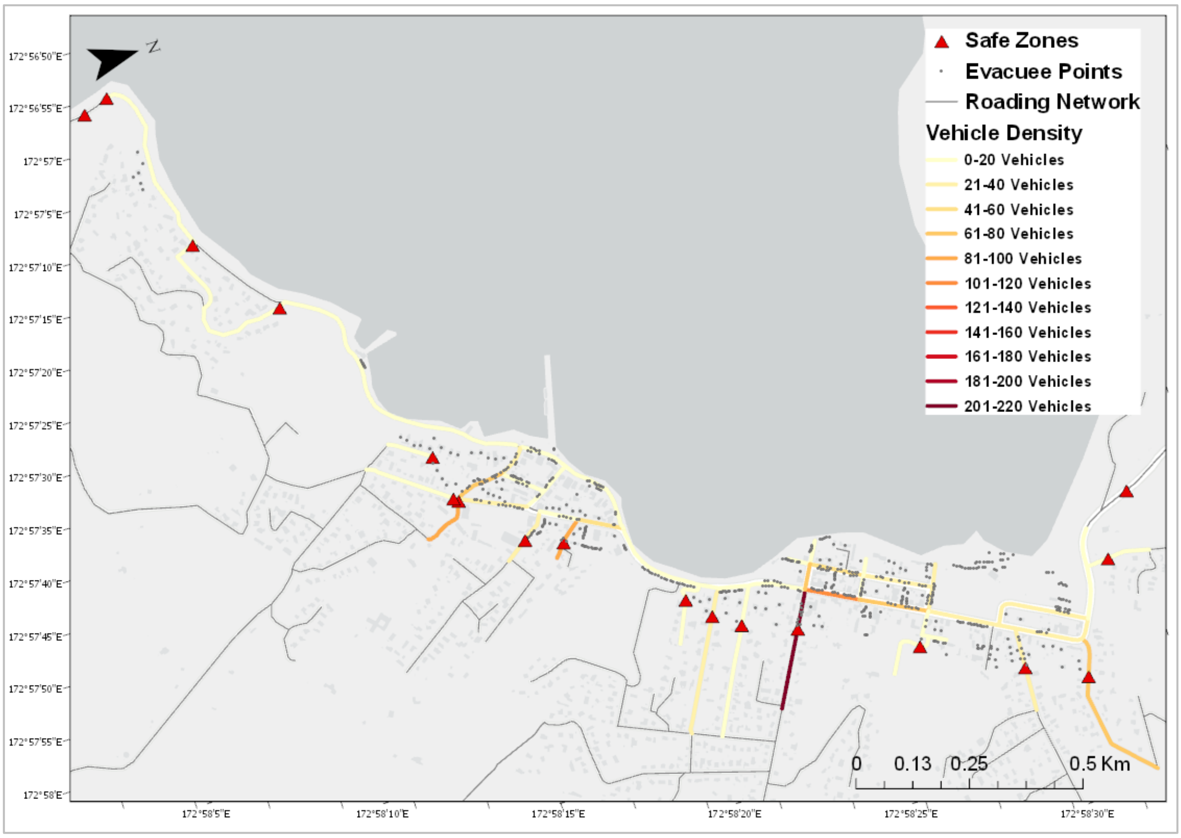

Figure 7.46: Vehicle density count results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

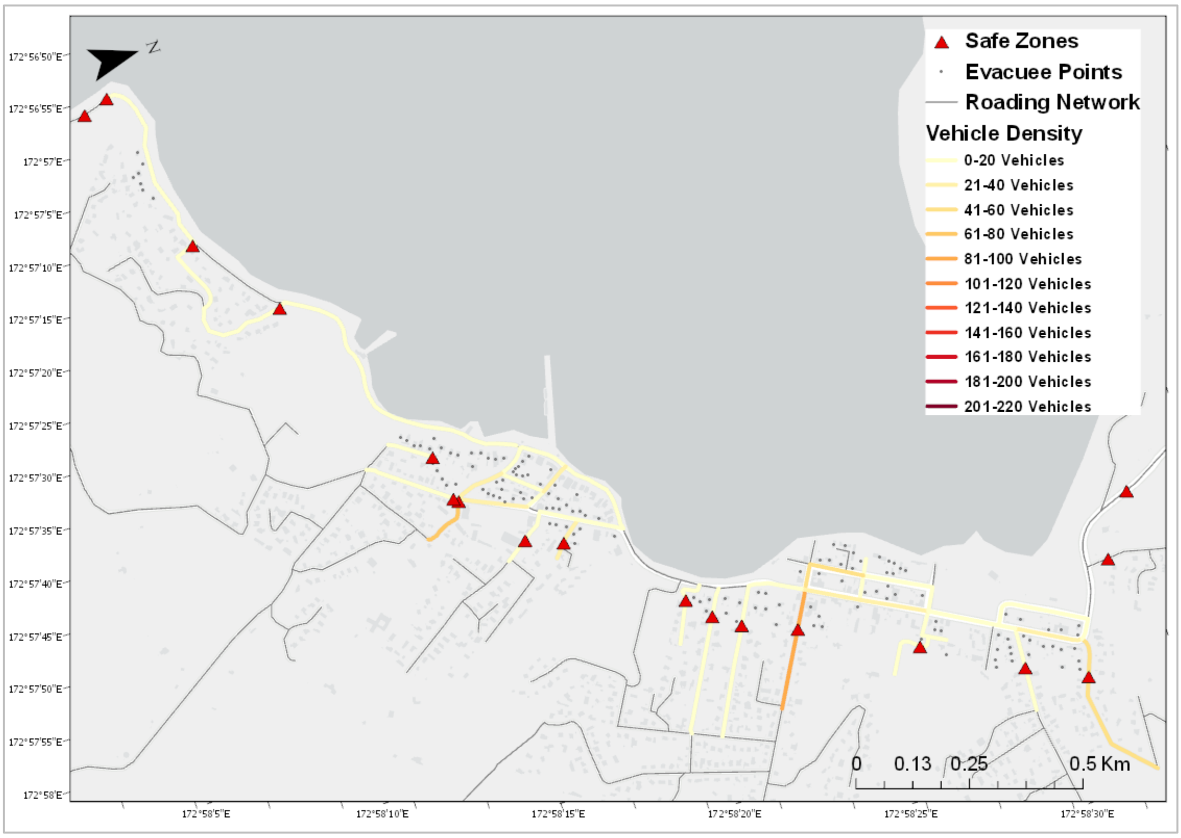

Figure 7.47: Vehicle density count results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

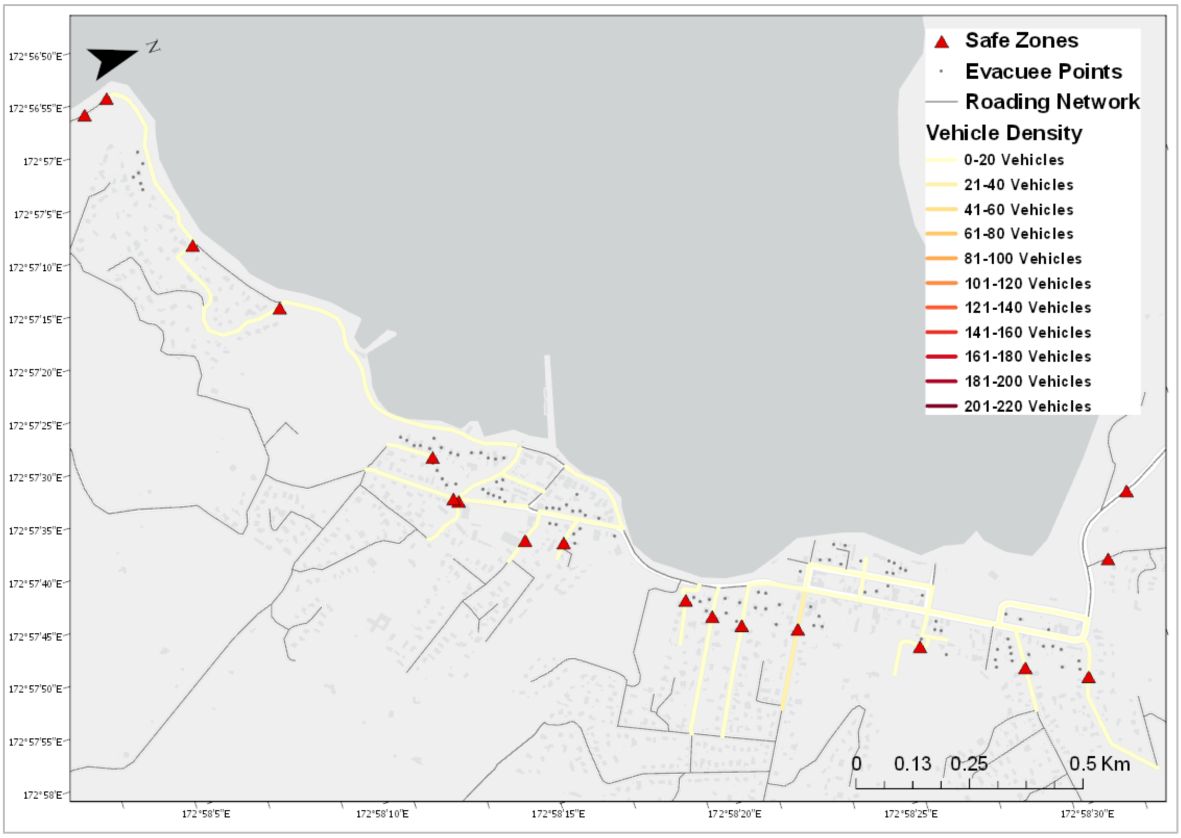

Figure 7.48: Vehicle density count results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

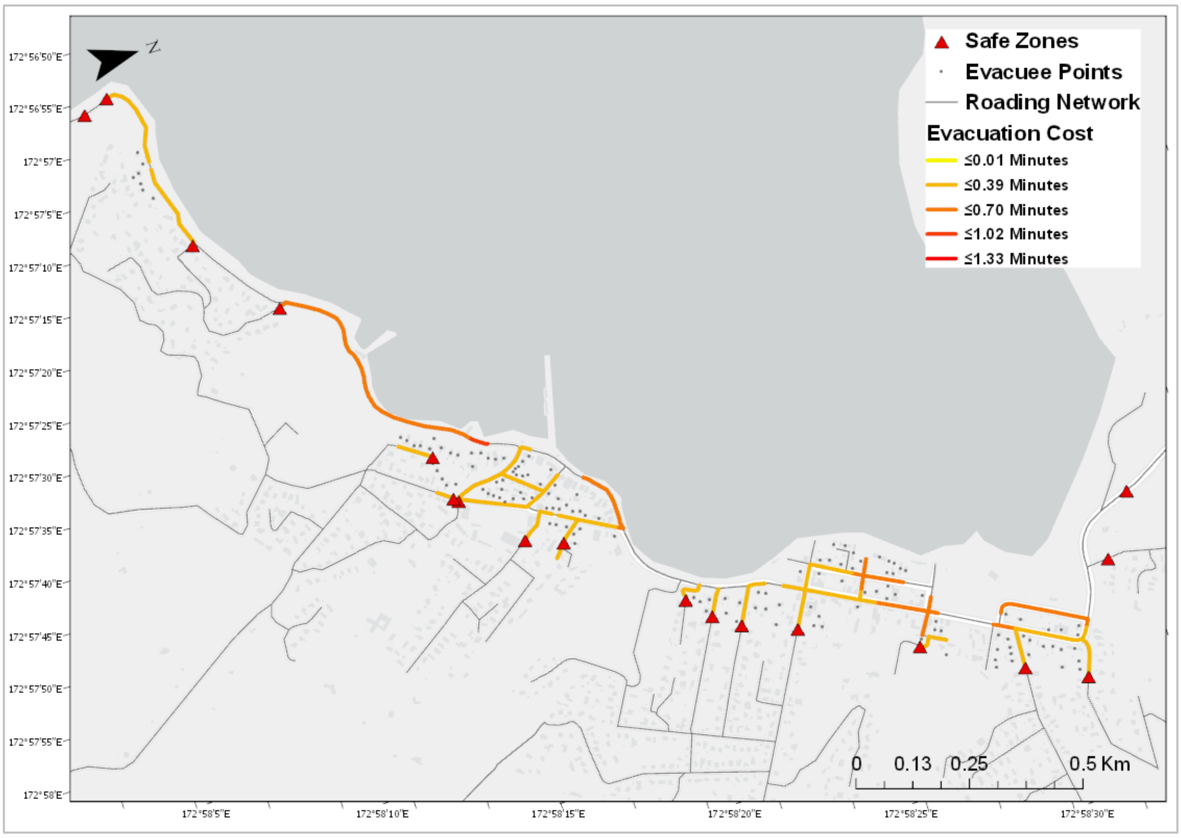

Figure 7.49: Evacuation cost results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

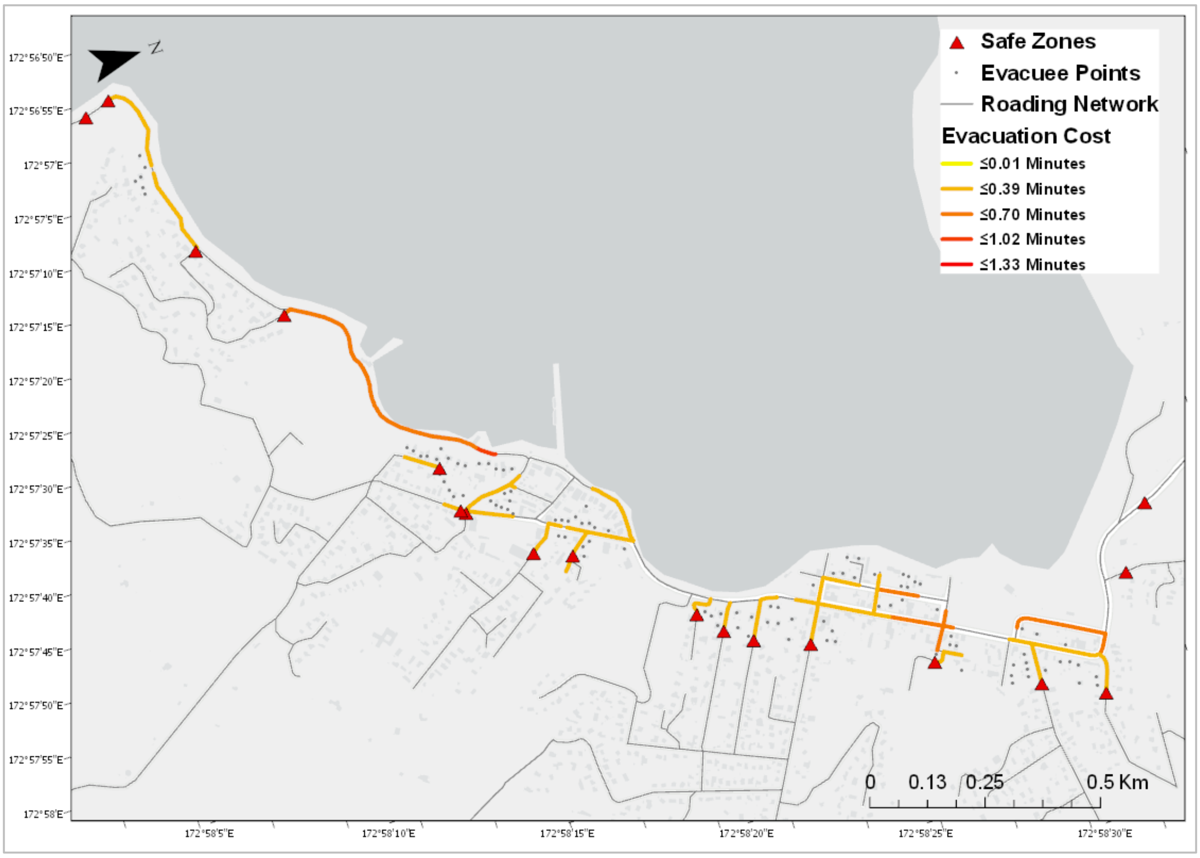

Figure 7.50: Evacuation cost results for Akaroa – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario

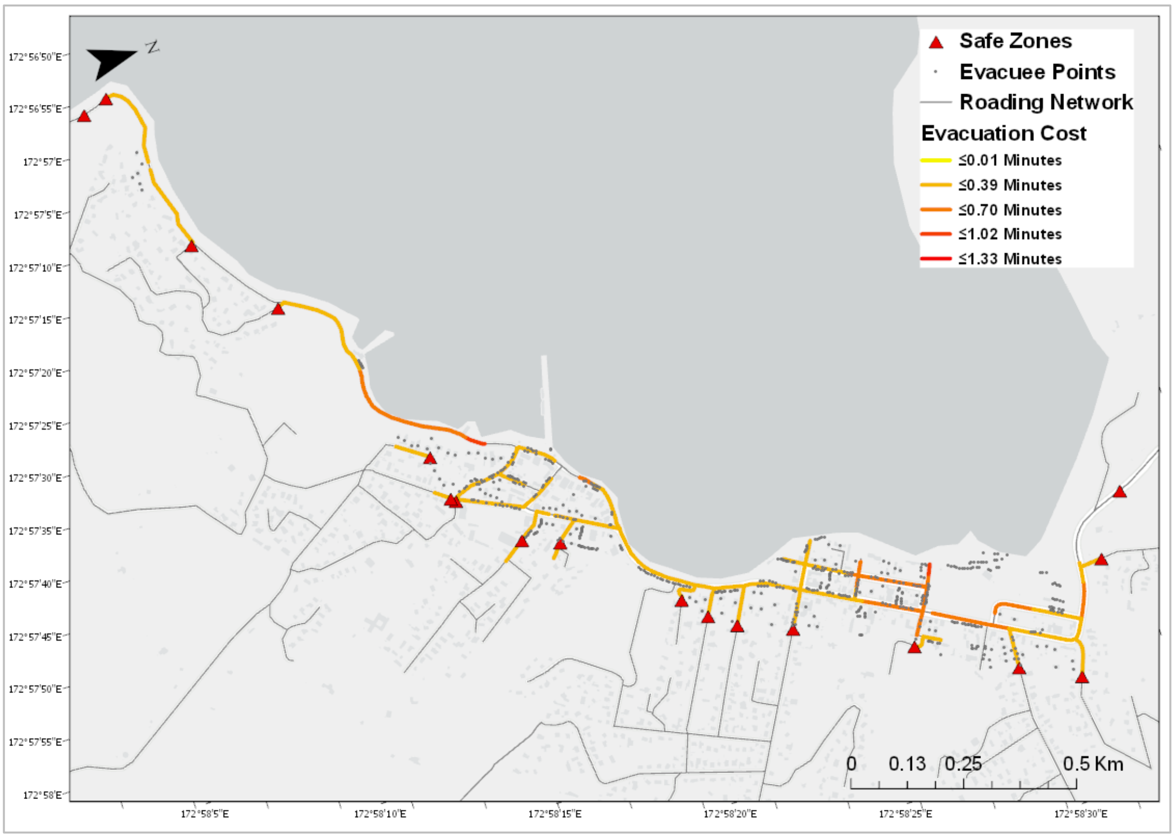

Figure 7.51: Evacuation cost results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

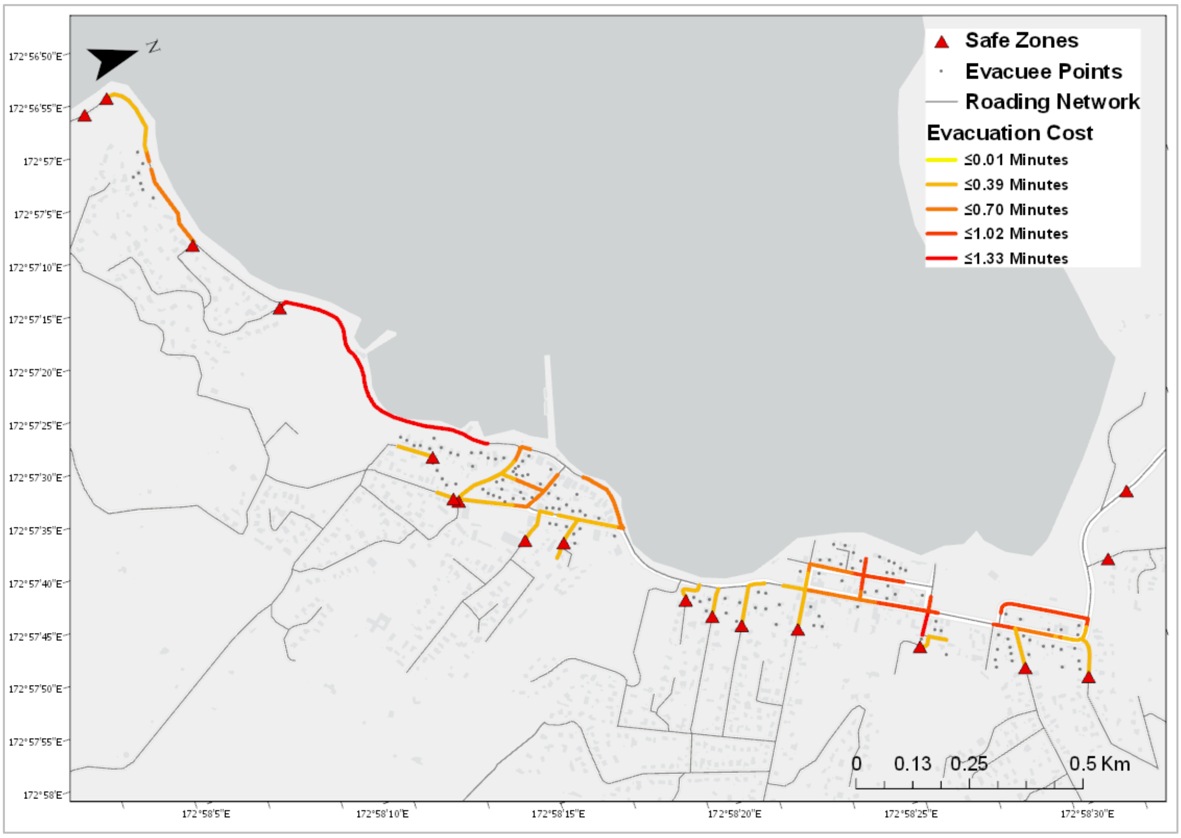

Figure 7.52: Evacuation cost results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

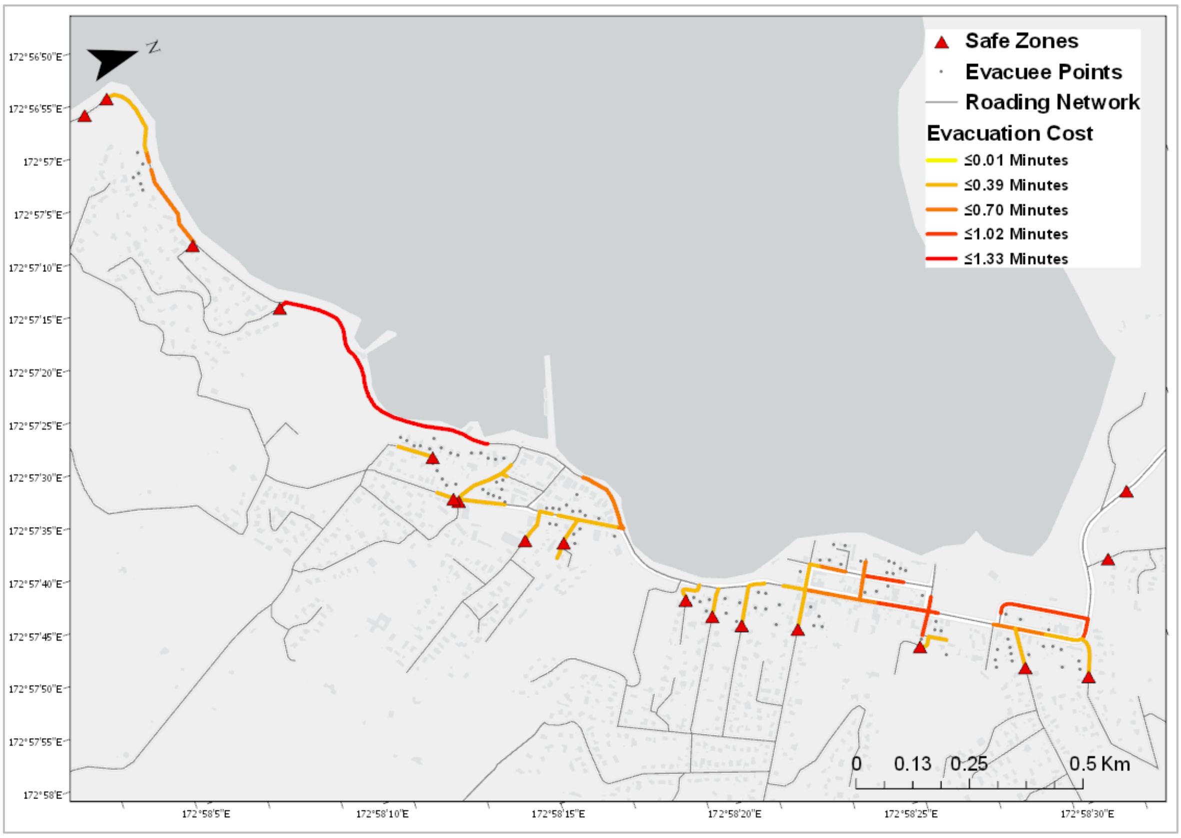

Figure 7.53: Evacuation cost results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

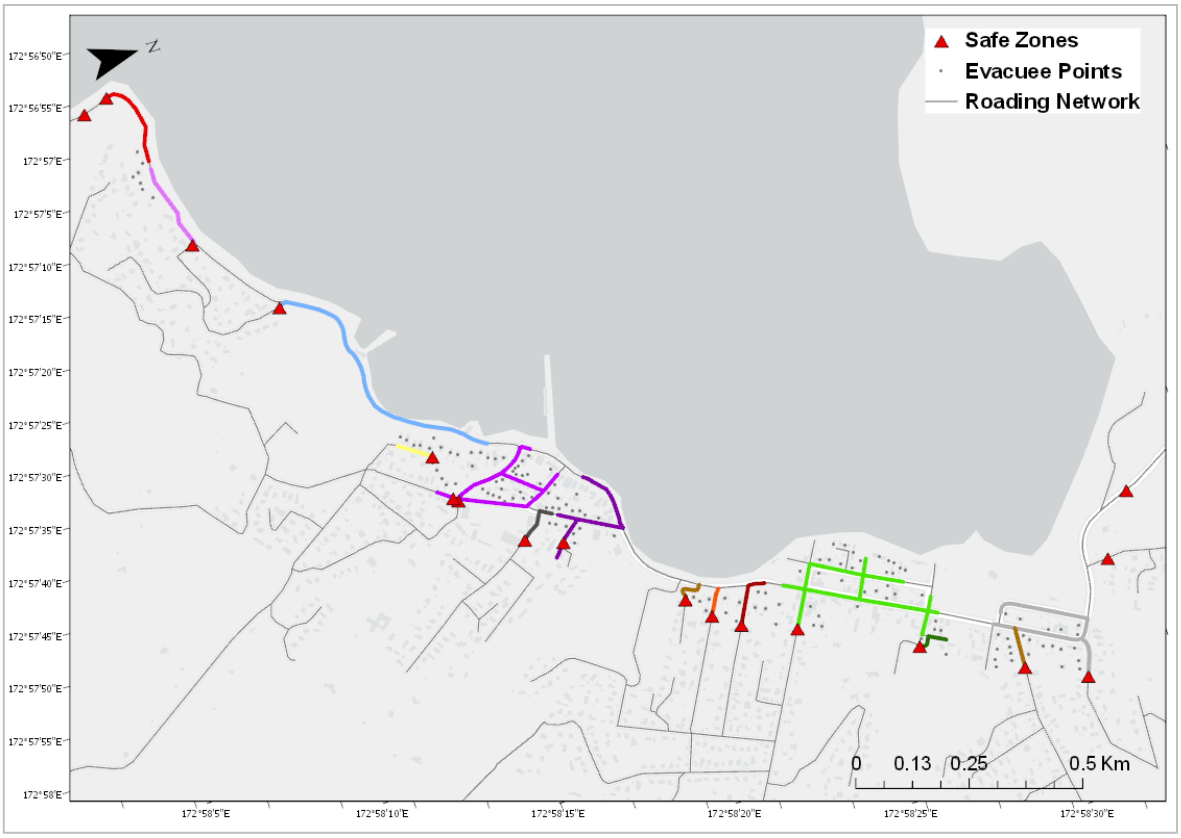

Figure 7.54: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

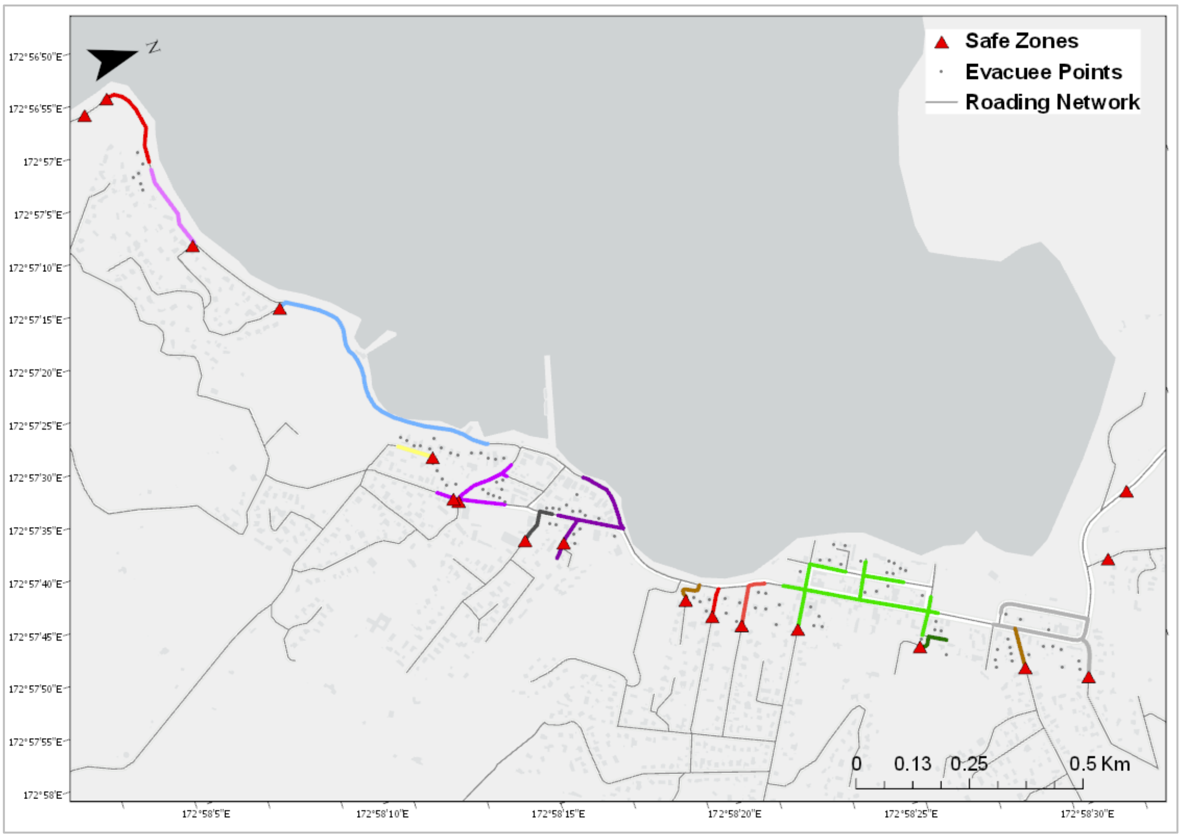

Figure 7.55: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

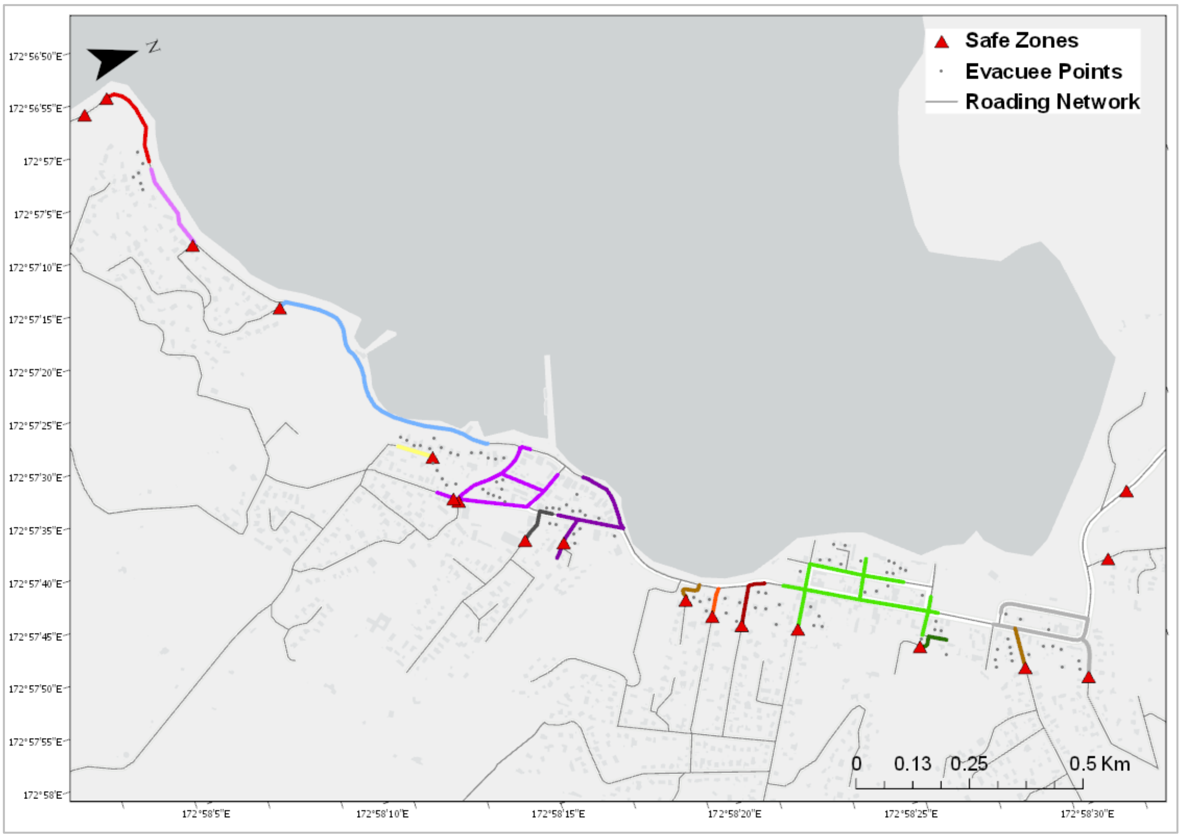

Figure 7.56: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

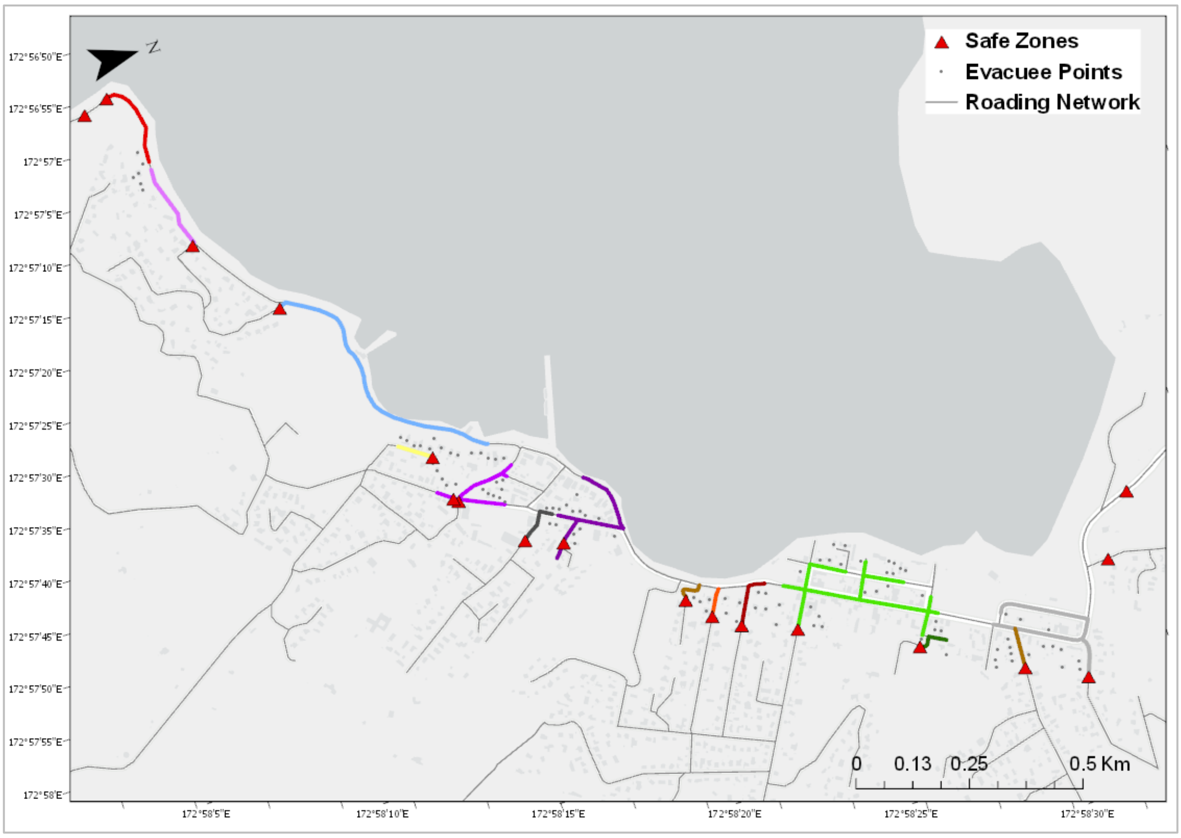

Figure 7.57: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

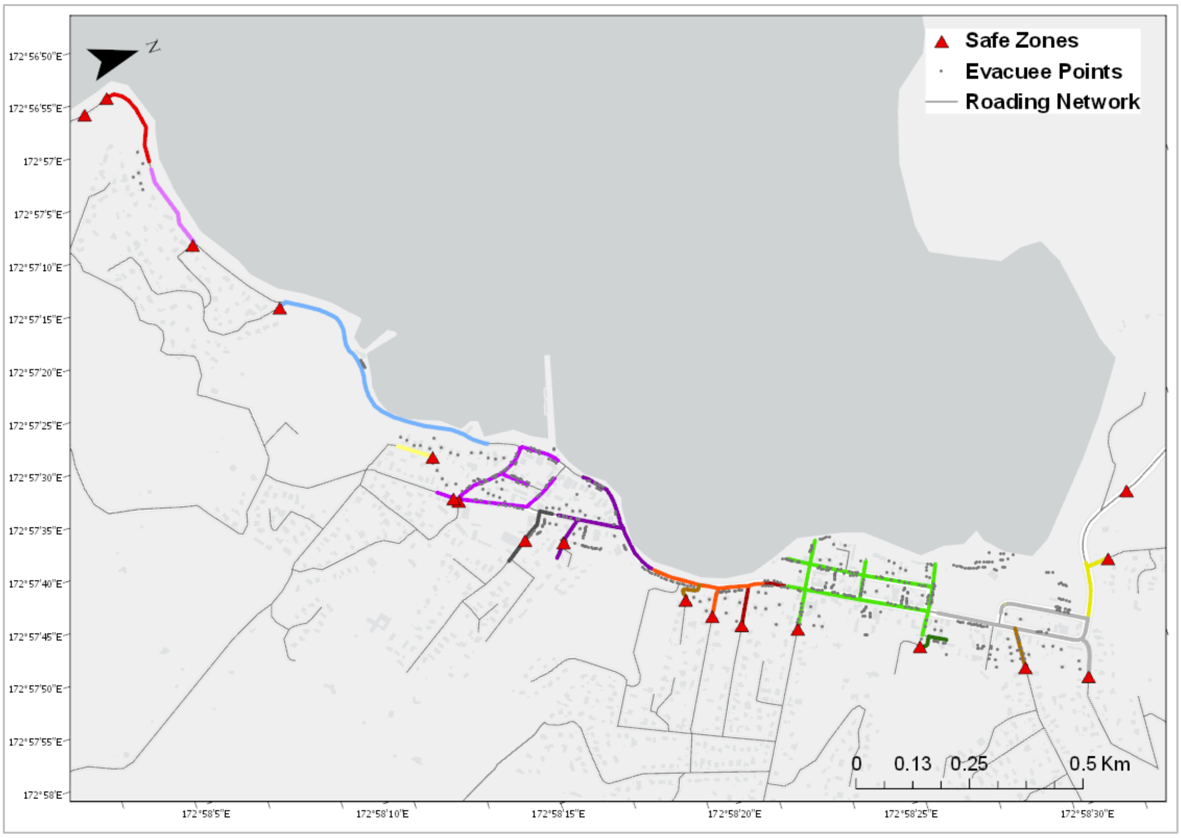

Figure 7.58: Safe zone distribution results for Akaroa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

iii. Reduced Safe Zones

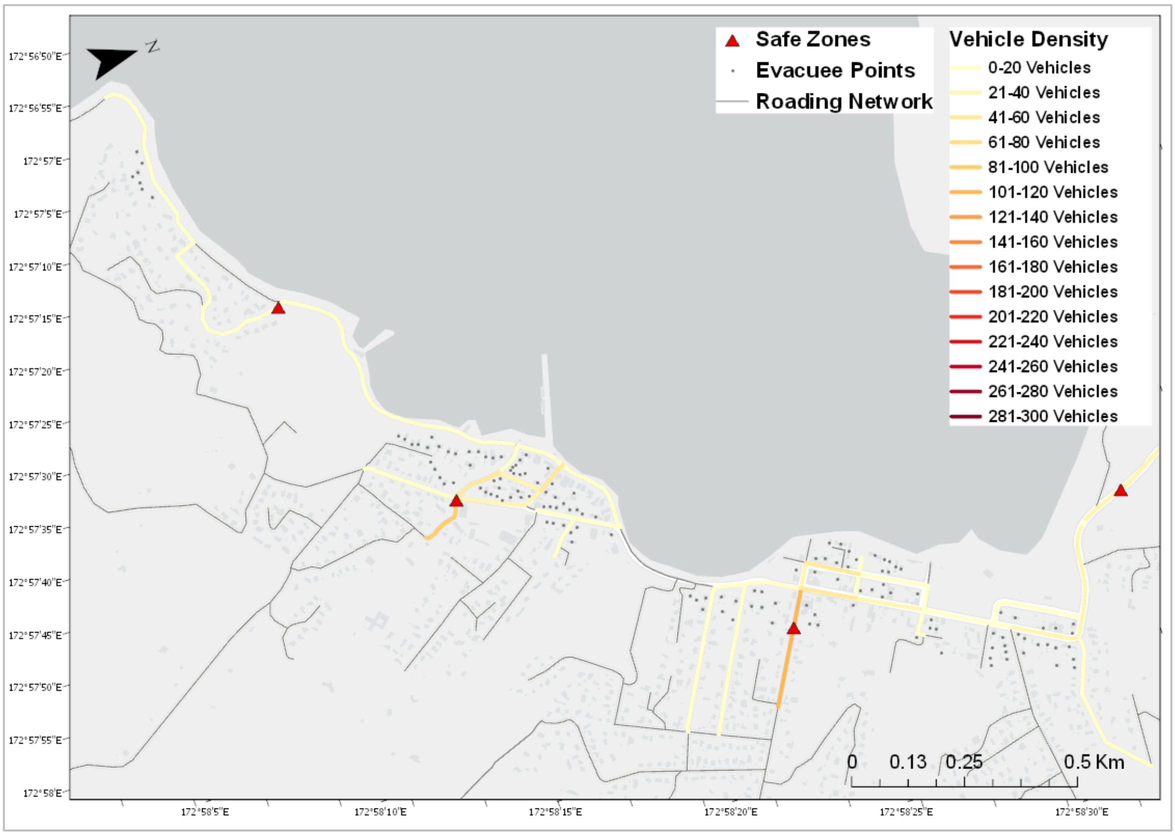

Figure 7.59: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

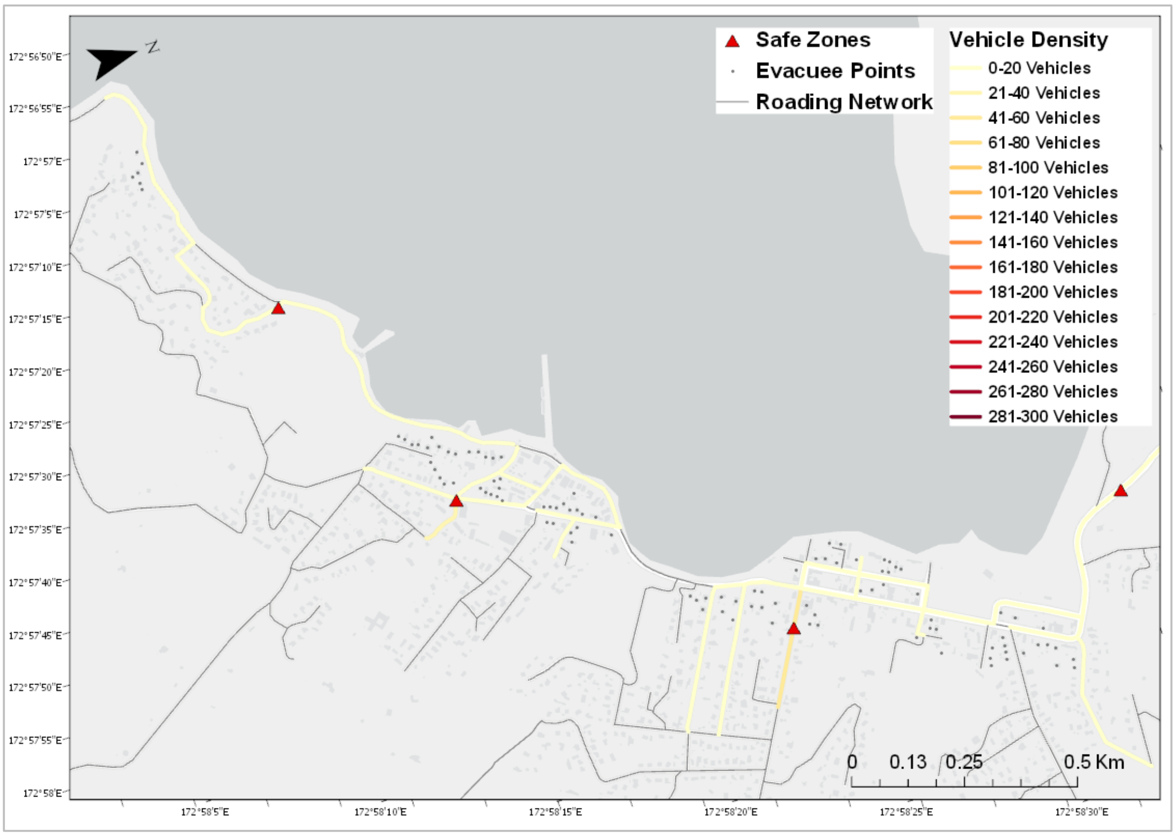

Figure 7.60: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

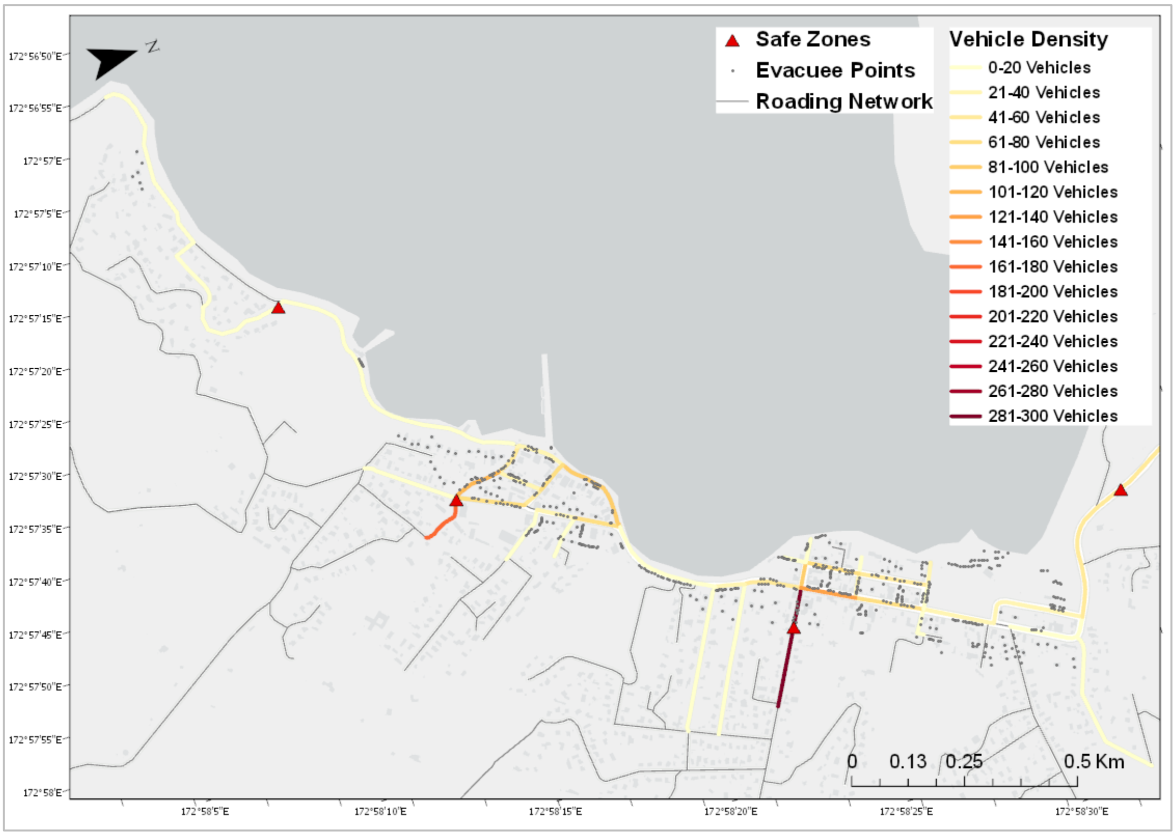

Figure 7.61: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

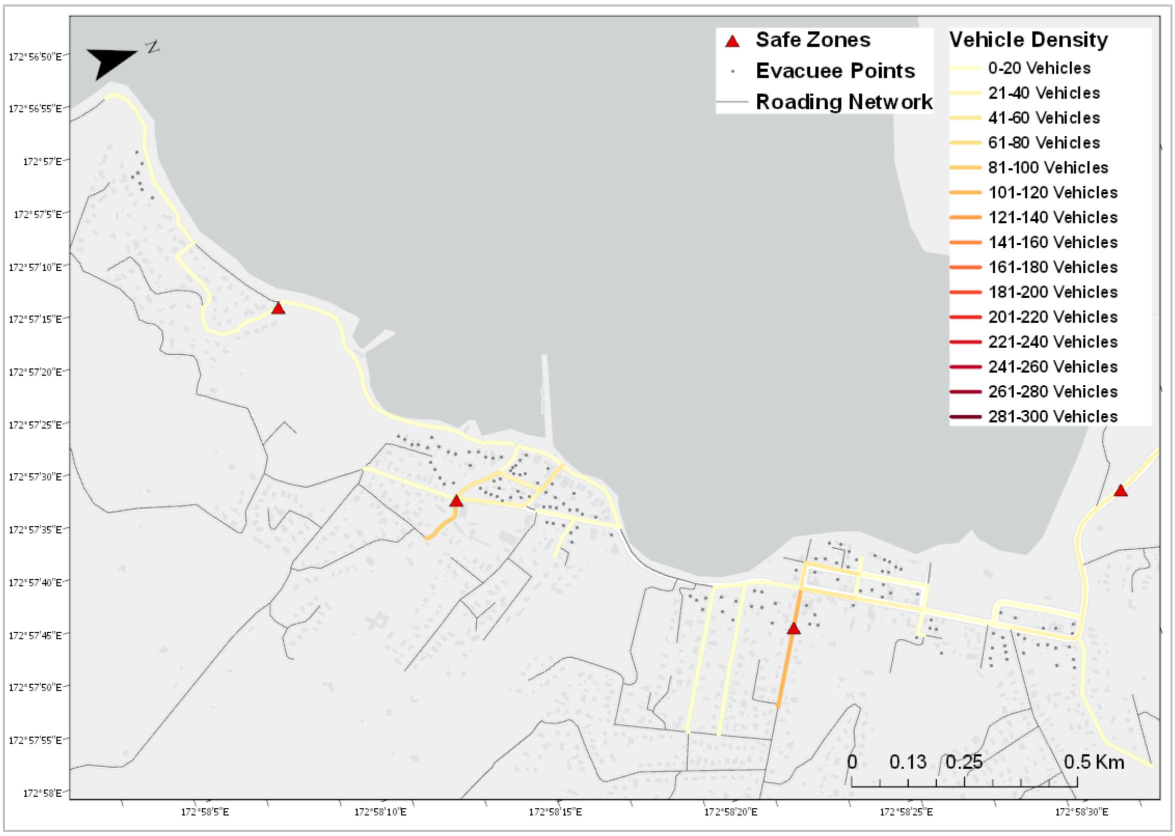

Figure 7.62: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

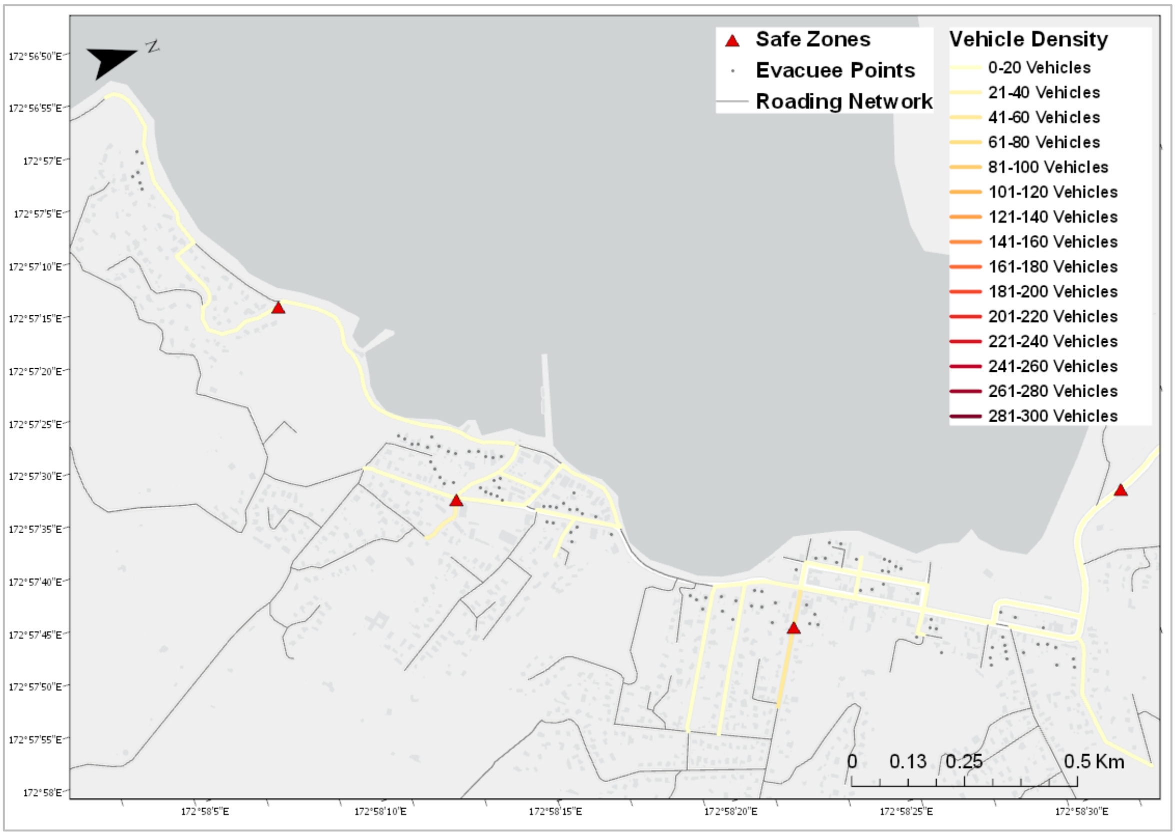

Figure 7.63: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

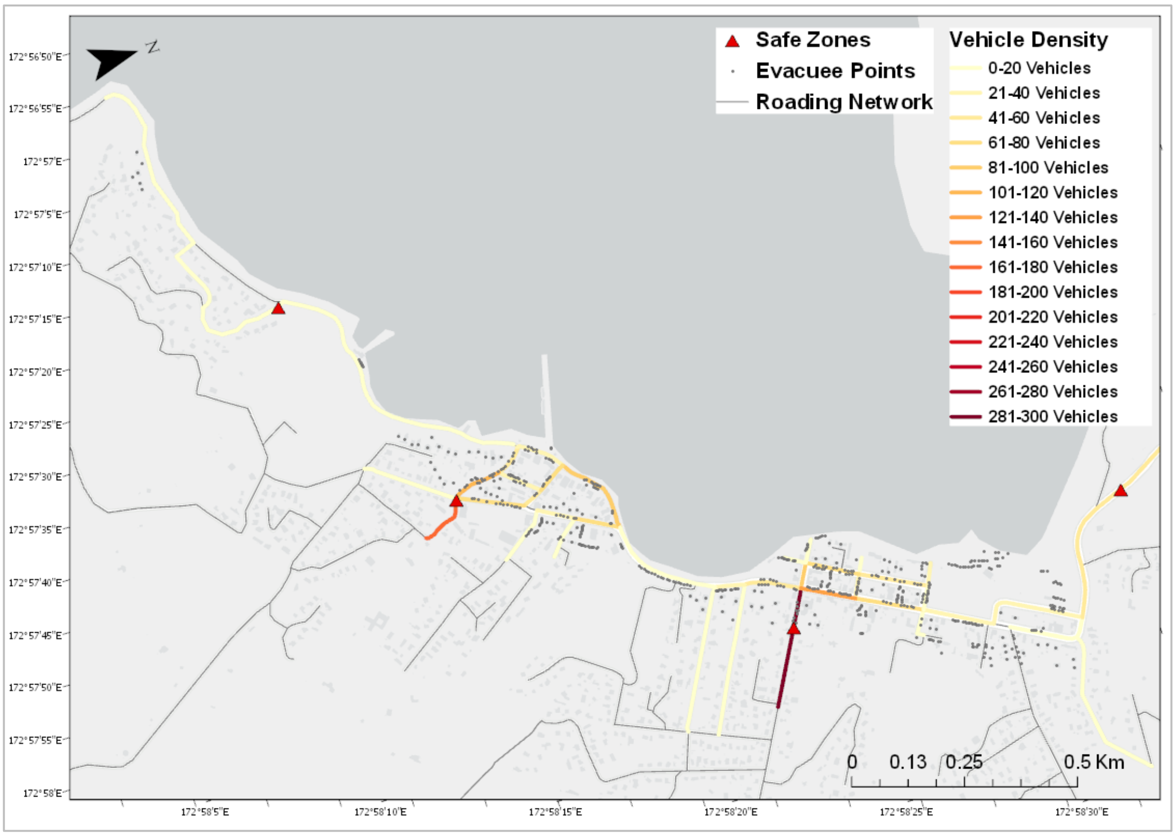

Figure 7.64: Vehicle density count results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

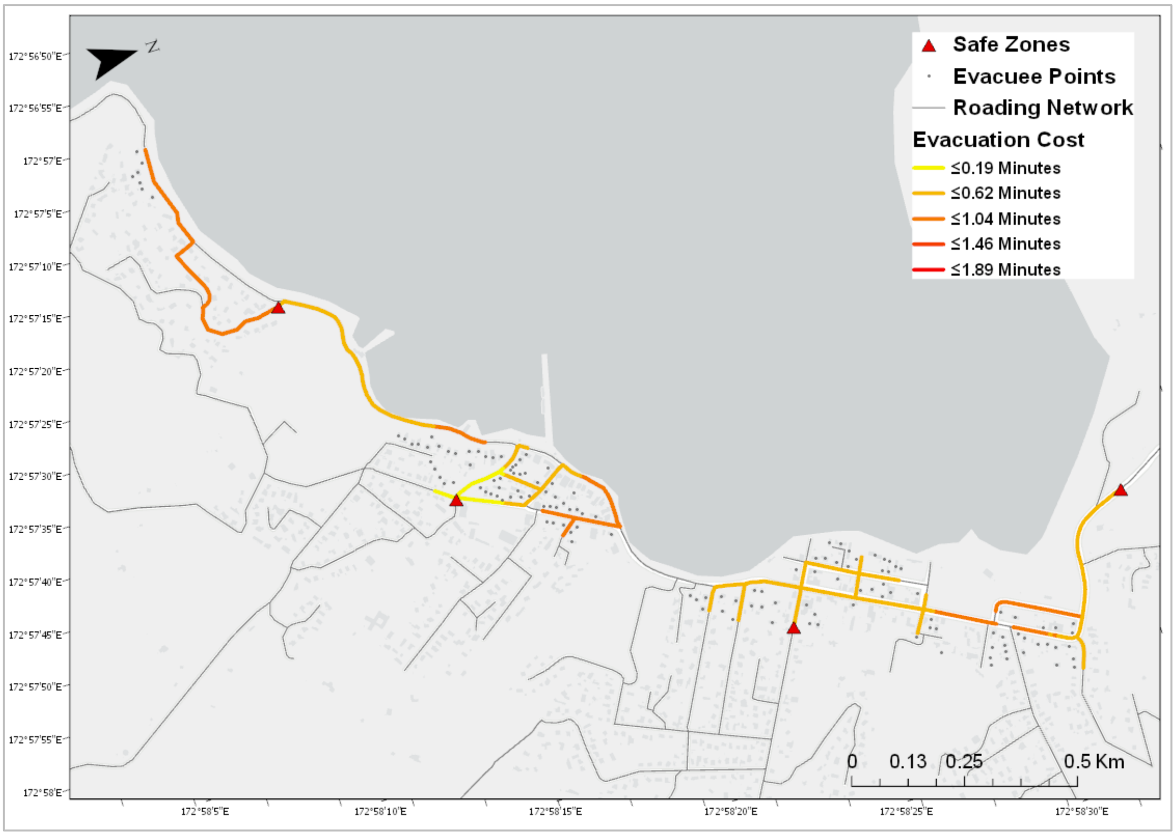

Figure 7.65: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

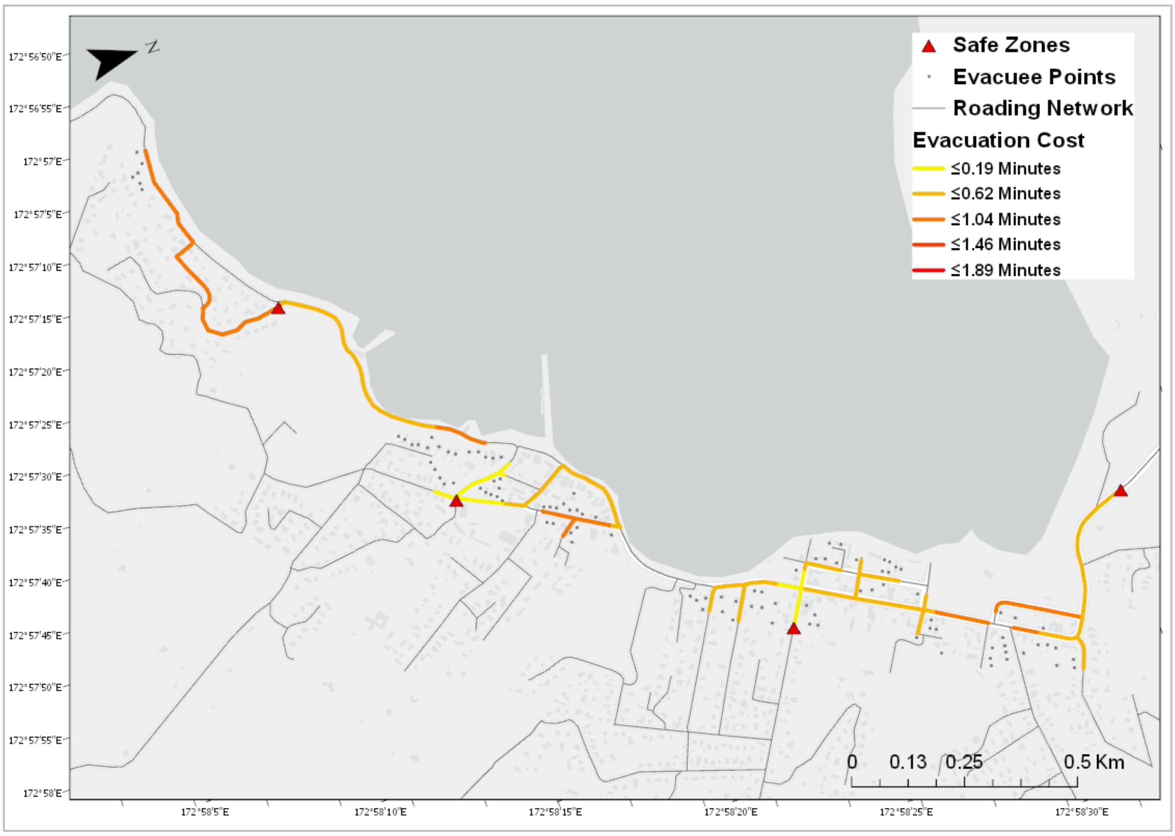

Figure 7.66: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

Figure 7.67: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

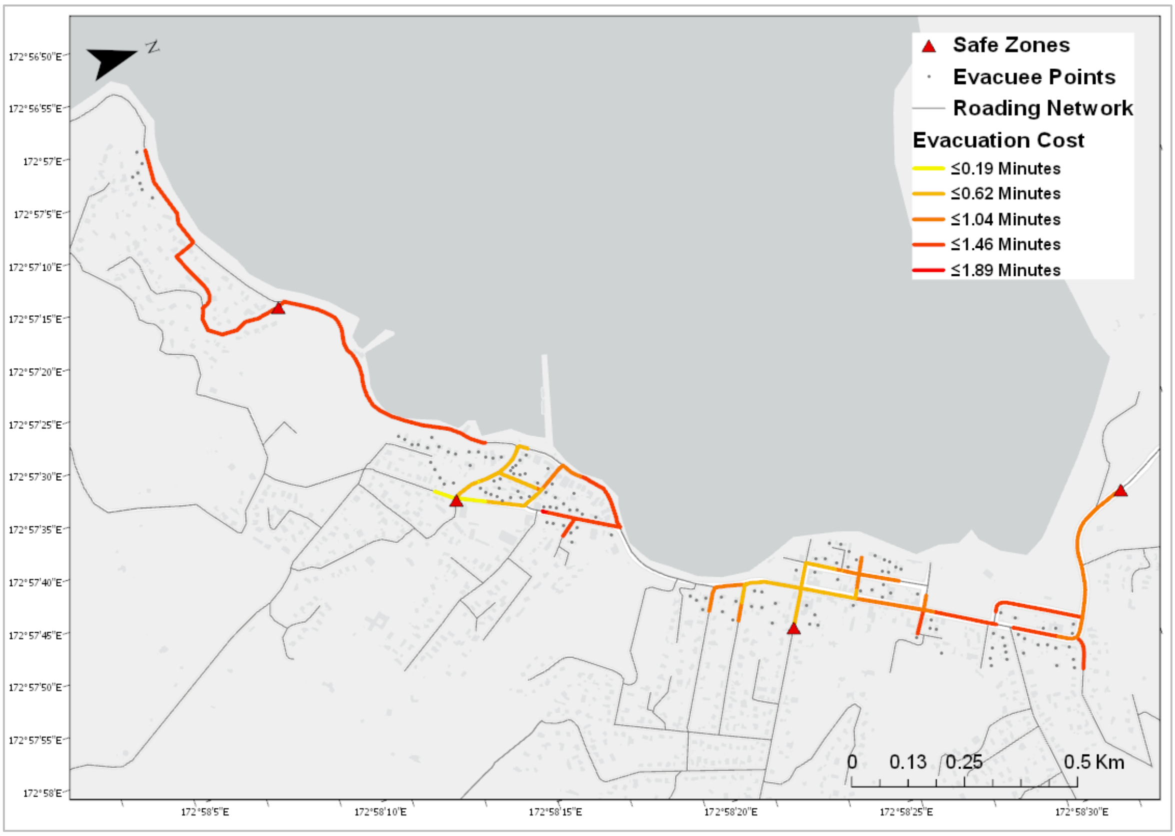

Figure 7.68: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

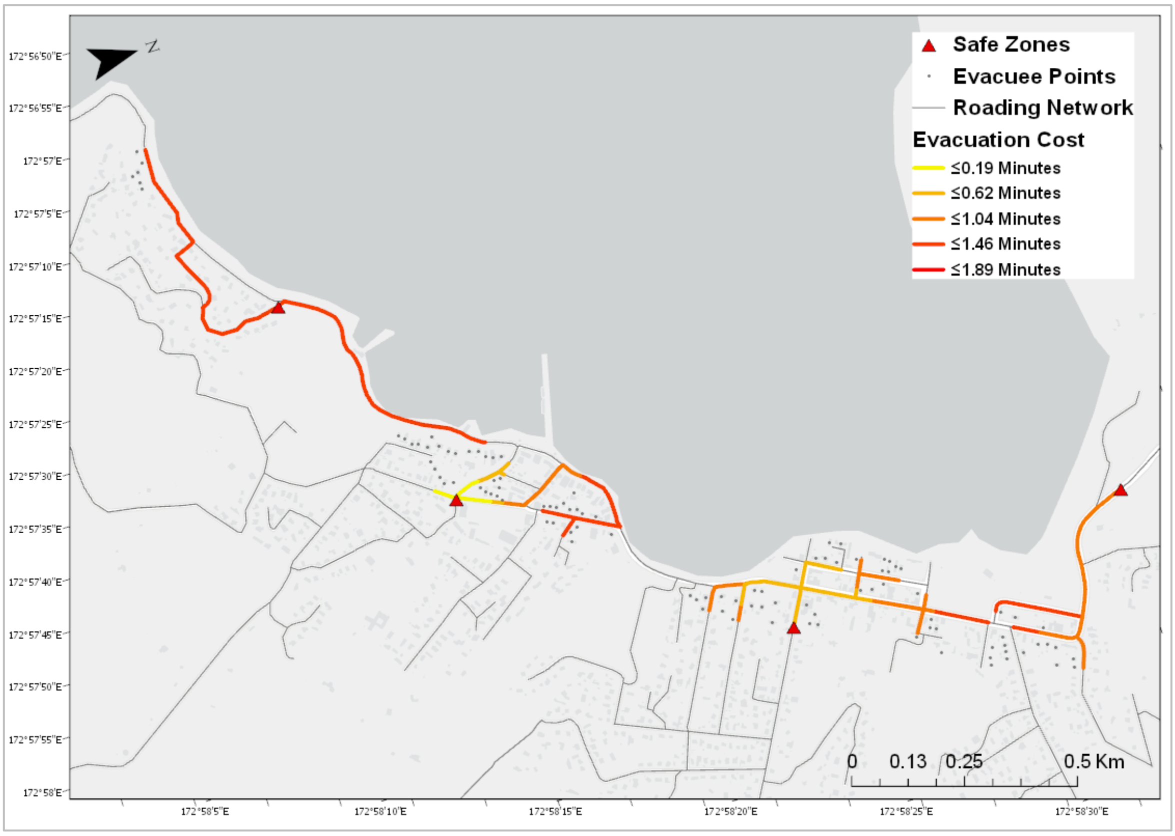

Figure 7.69: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

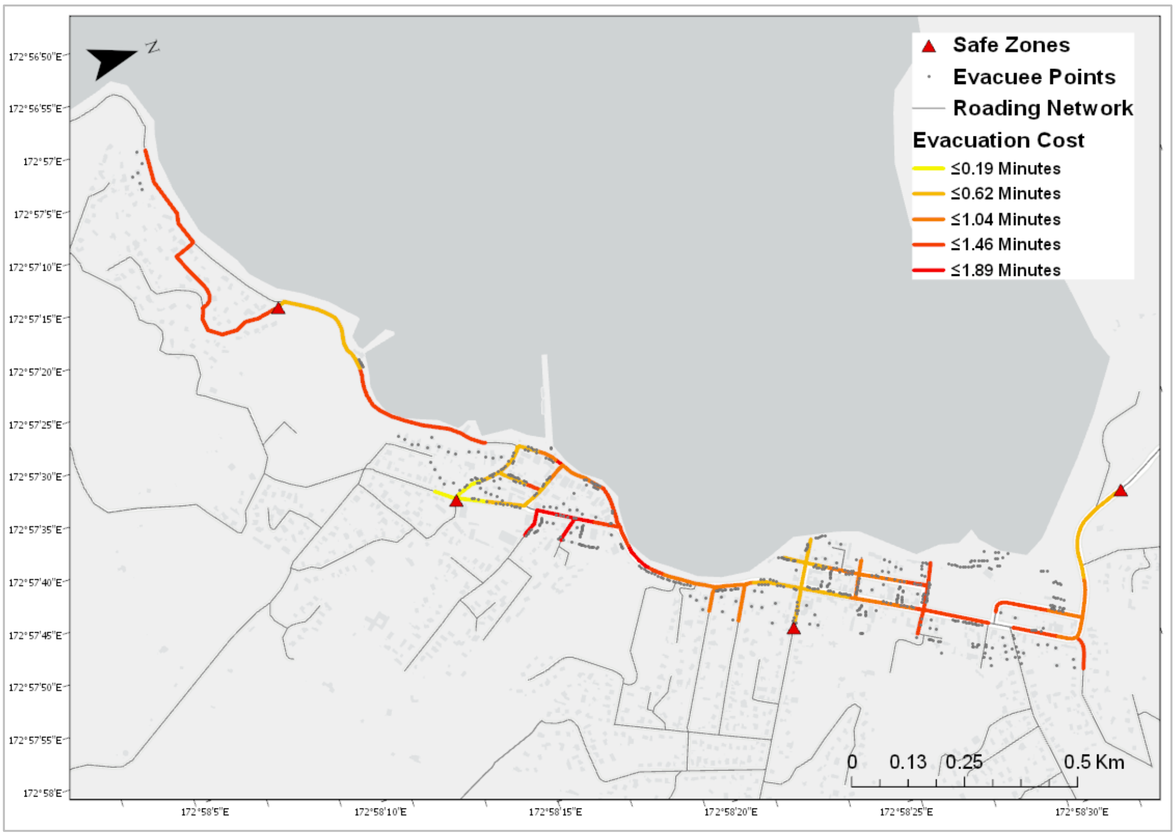

Figure 7.70: Evacuation cost results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

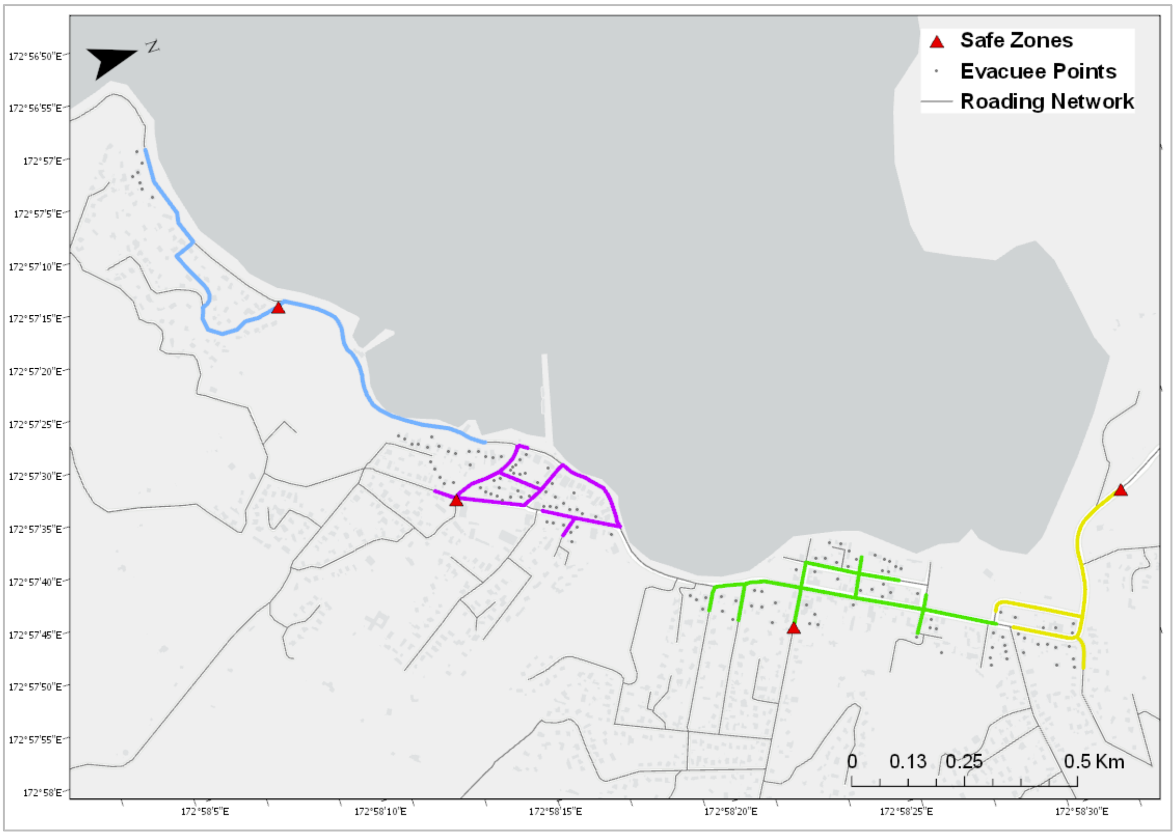

Figure 7.71: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

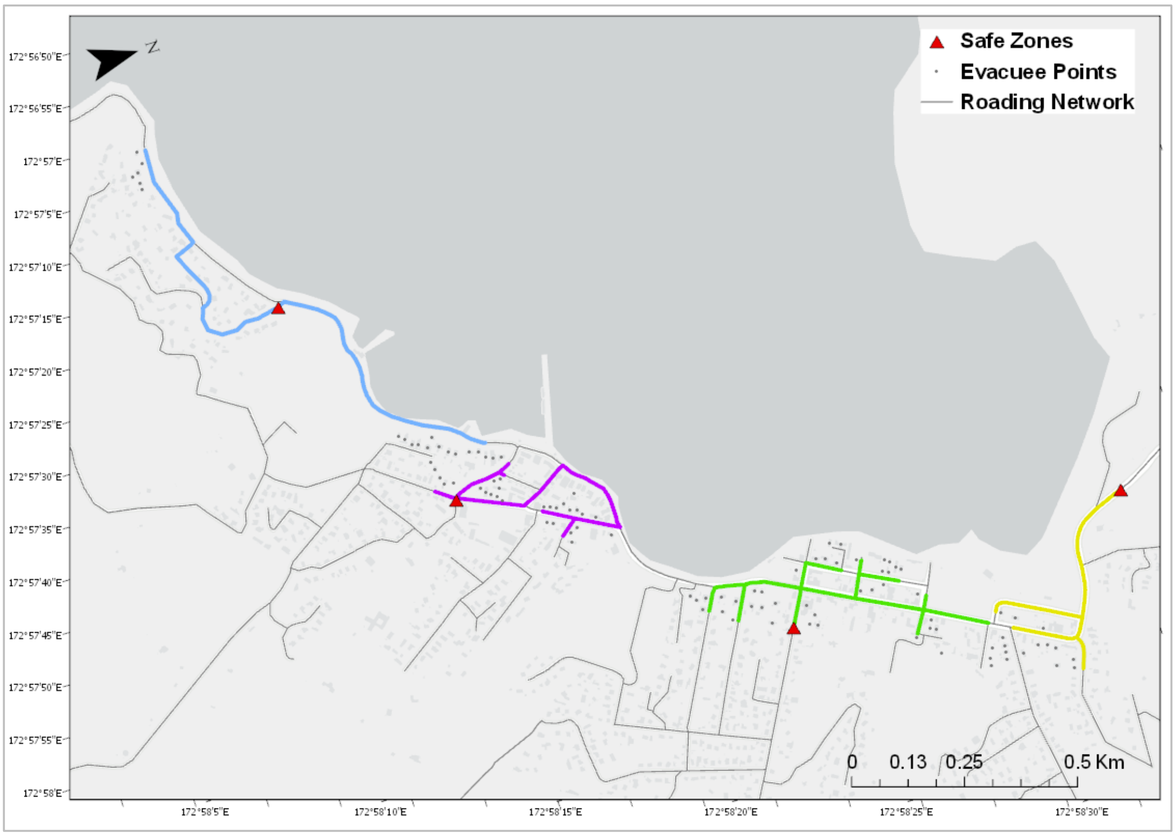

Figure 7.72: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

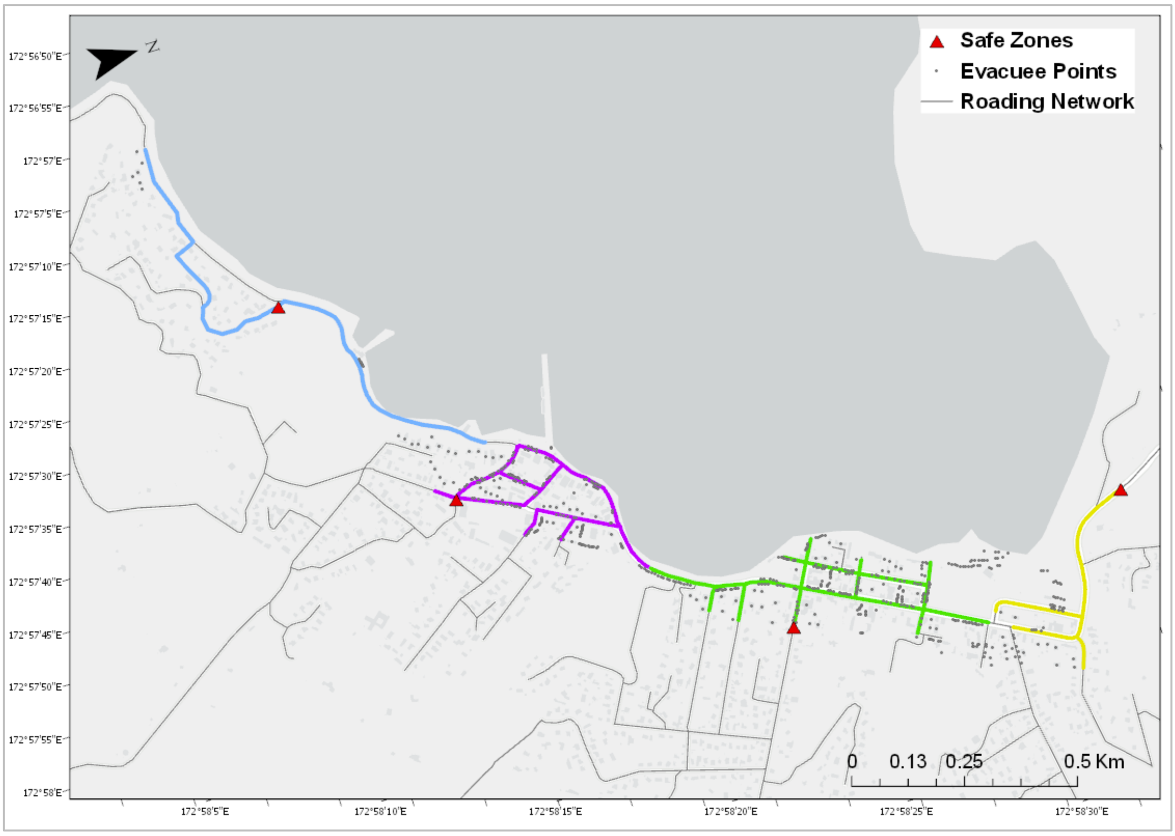

Figure 7.73: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

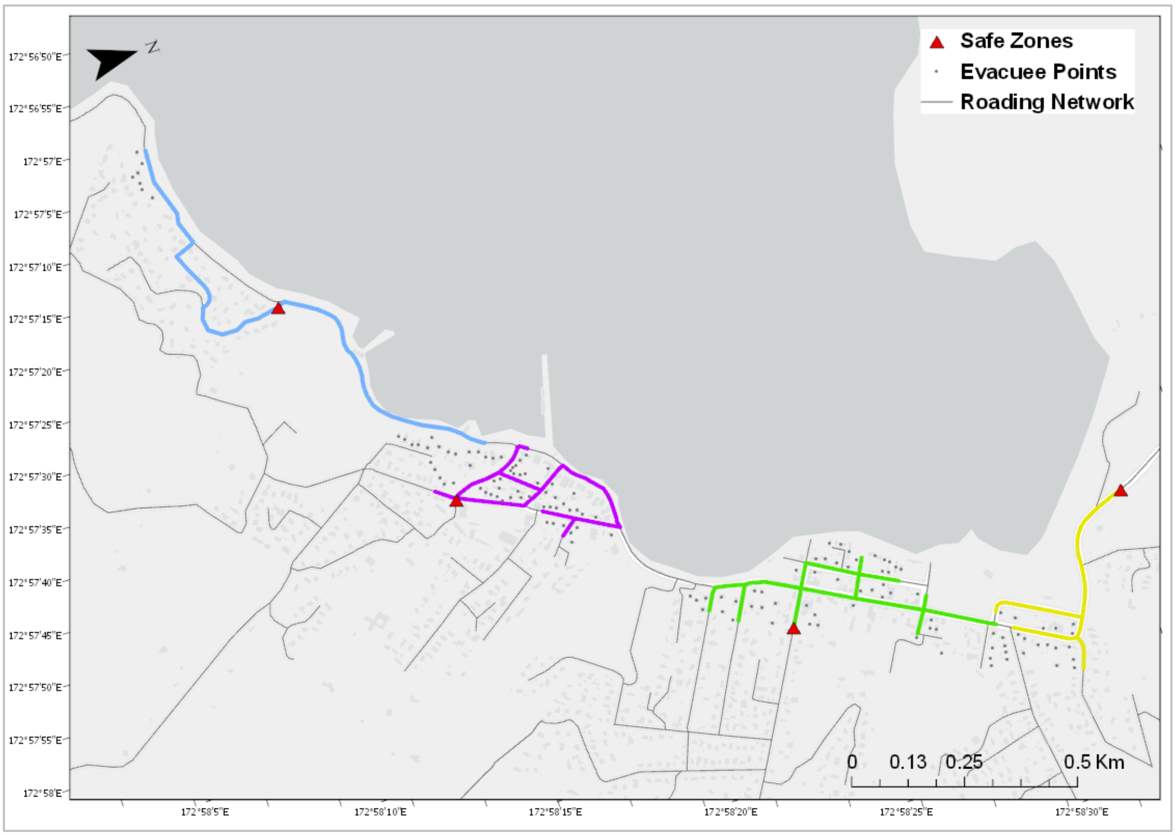

Figure 7.74: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

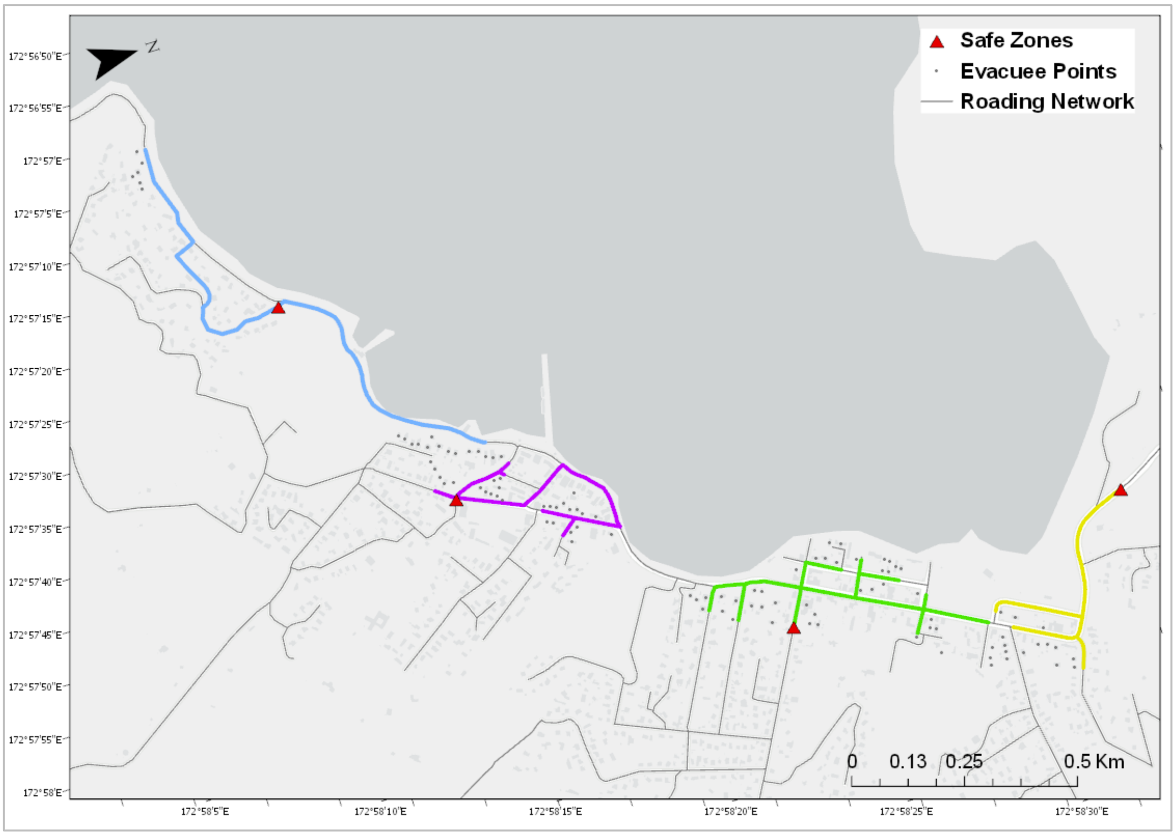

Figure 7.75: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

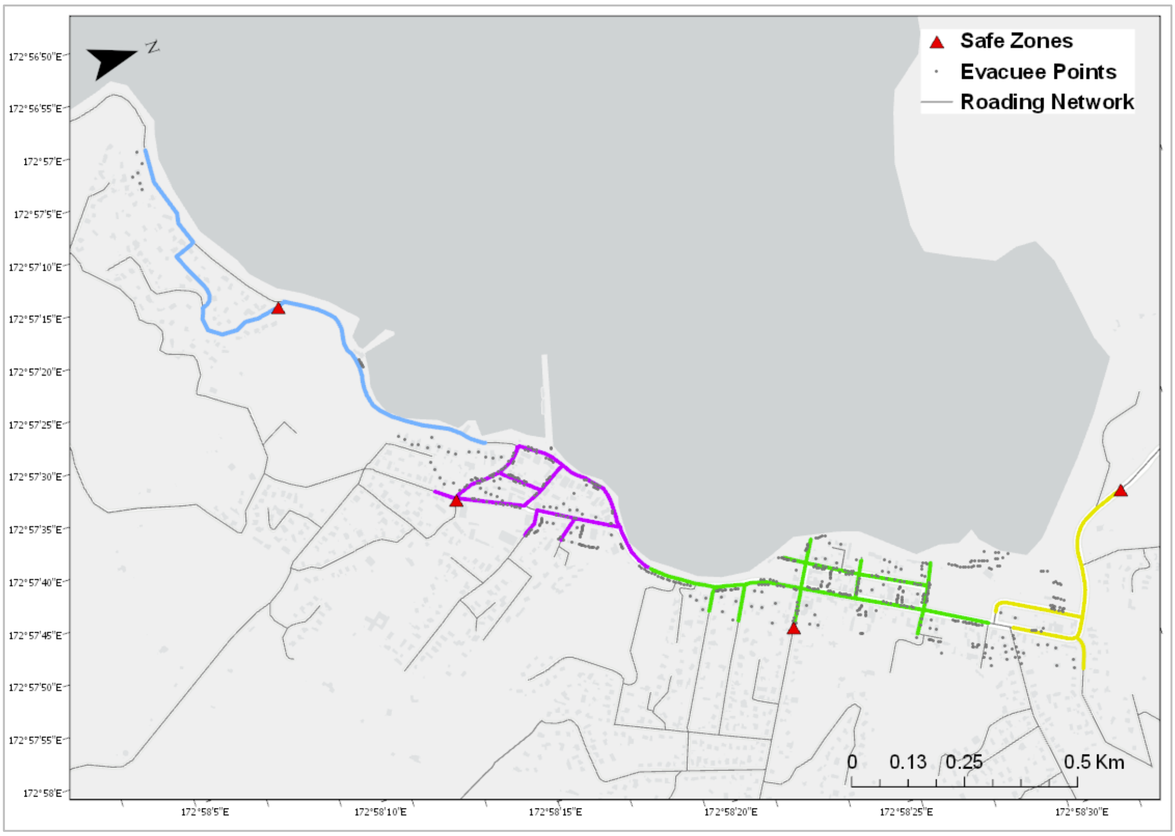

Figure 7.76: Safe zone distribution results for Akaroa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

b. Birdlings Flat

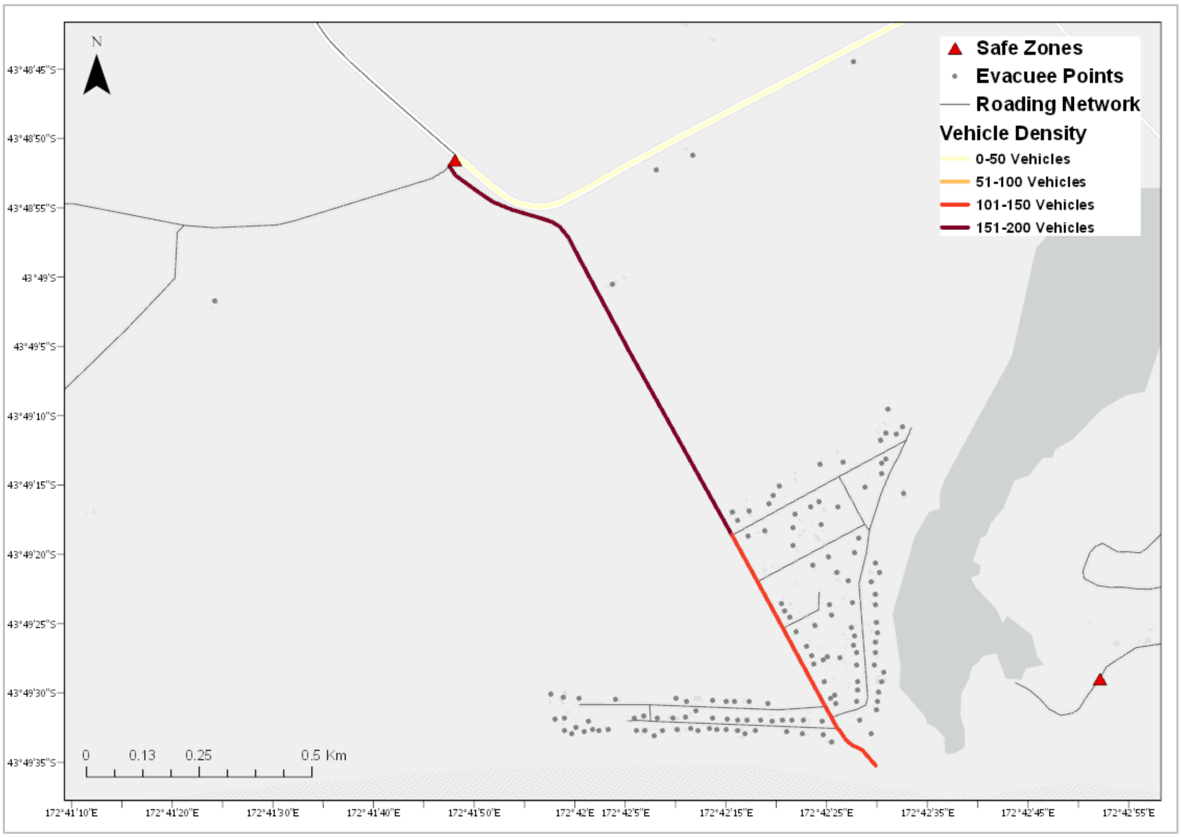

Figure 7.77: Vehicle density count results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

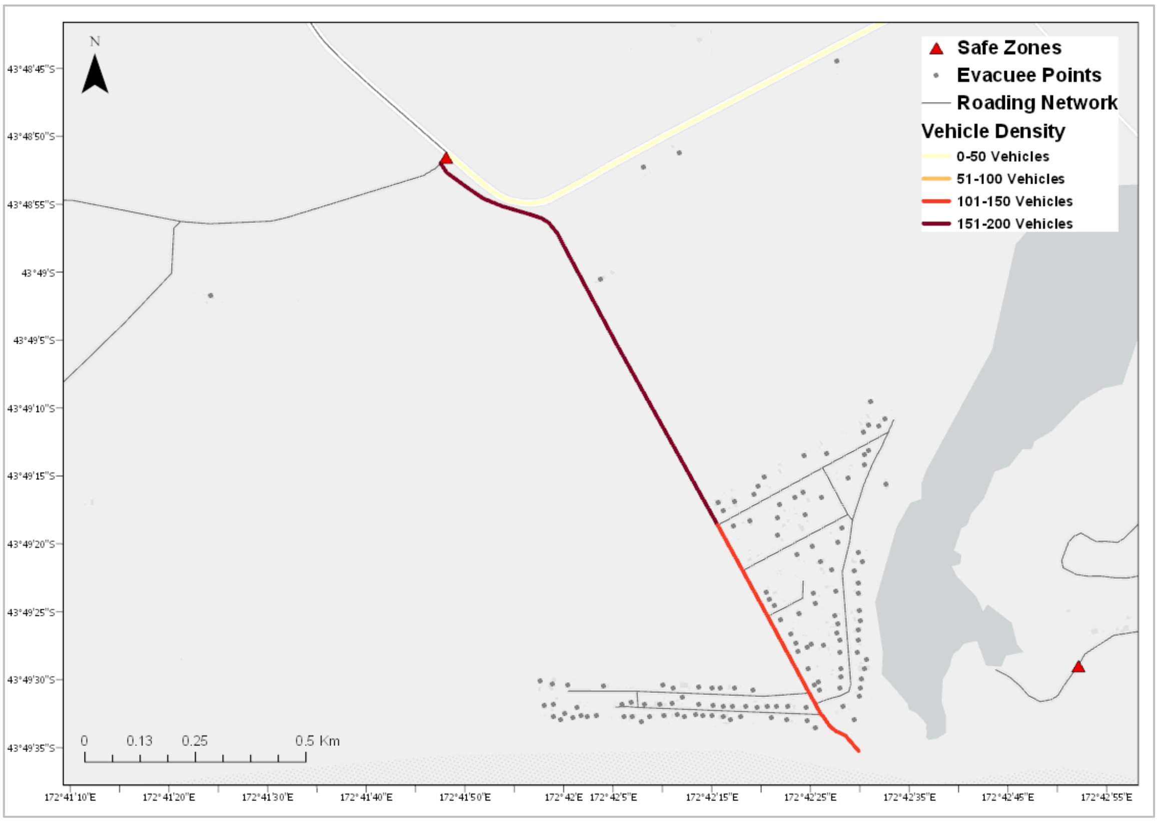

Figure 7.78: Vehicle density count results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

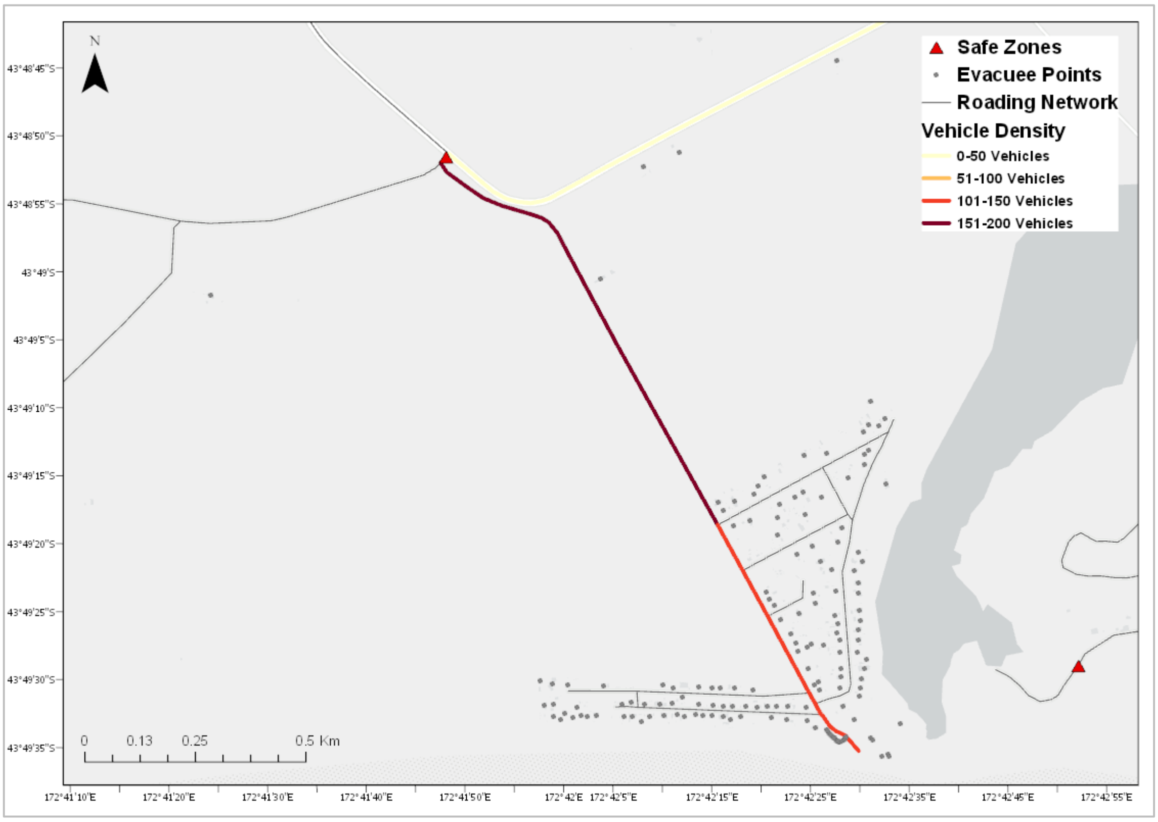

Figure 7.79: Vehicle density count results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

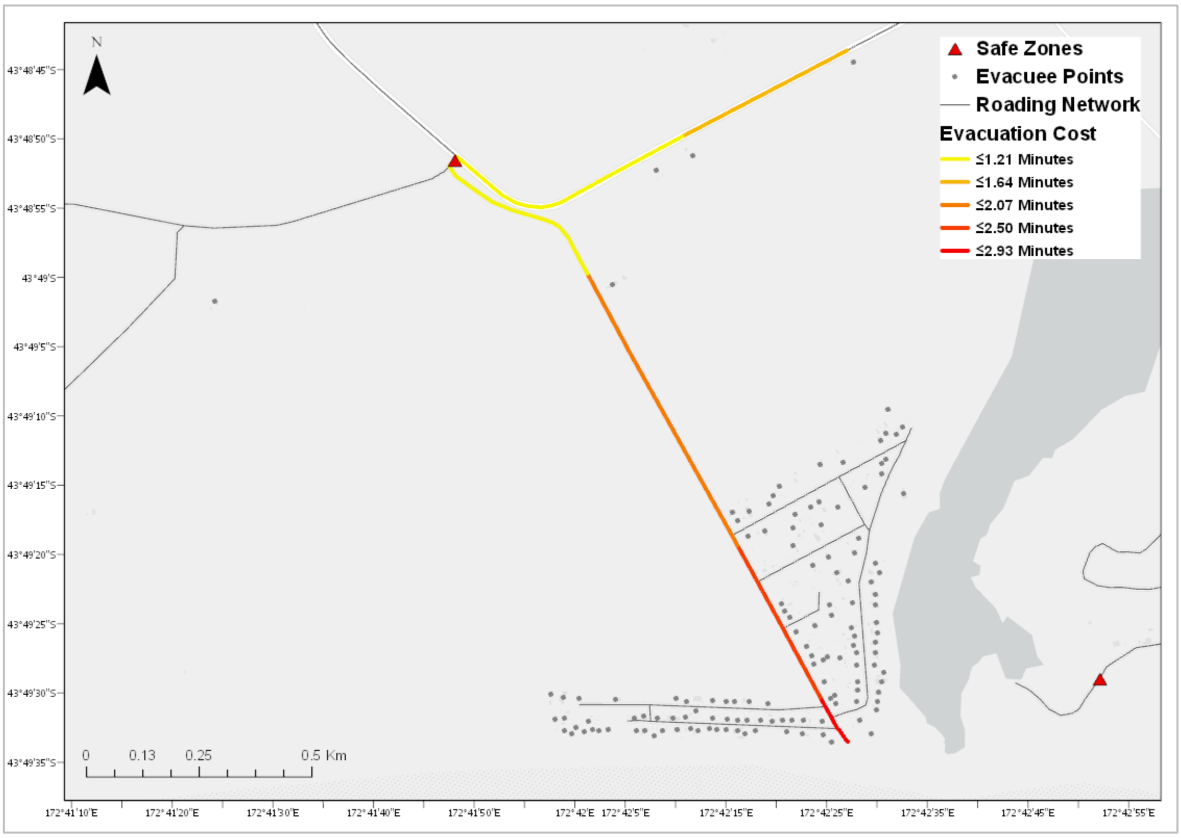

Figure 7.80: Evacuation cost results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

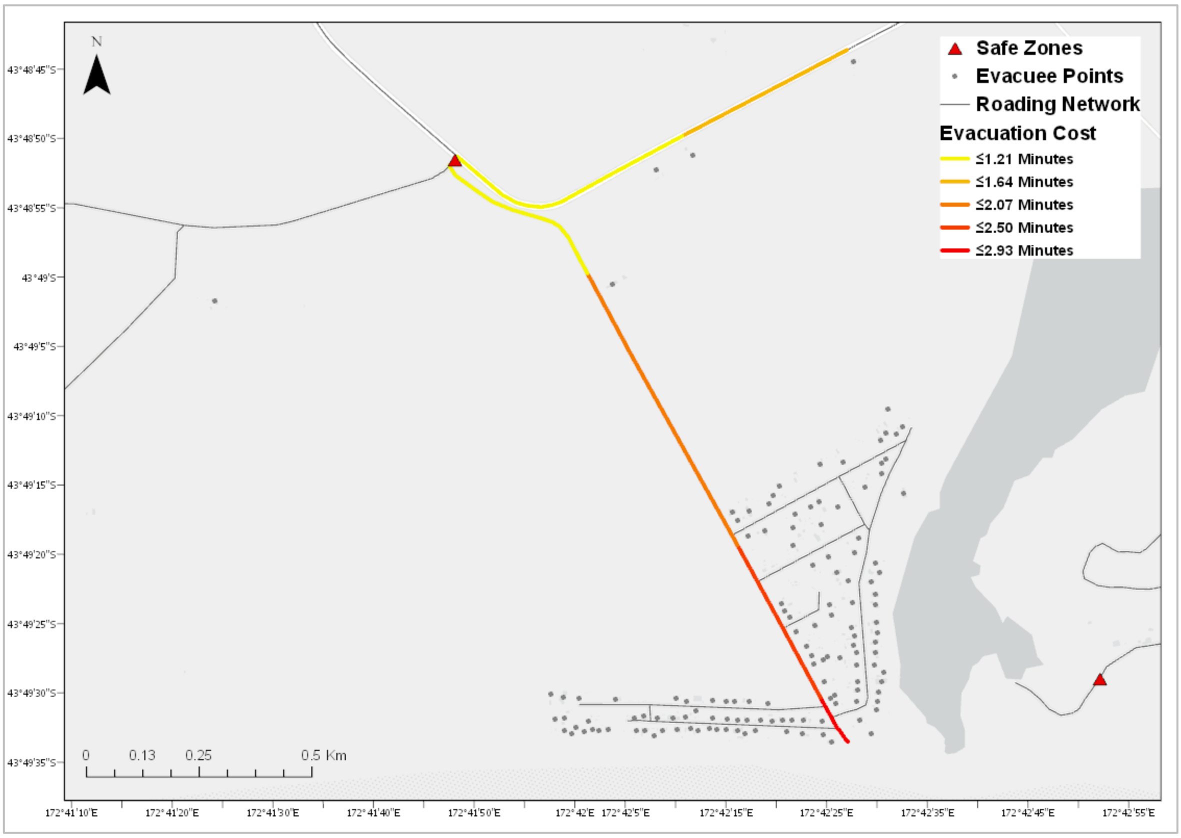

Figure 7.81: Evacuation cost results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

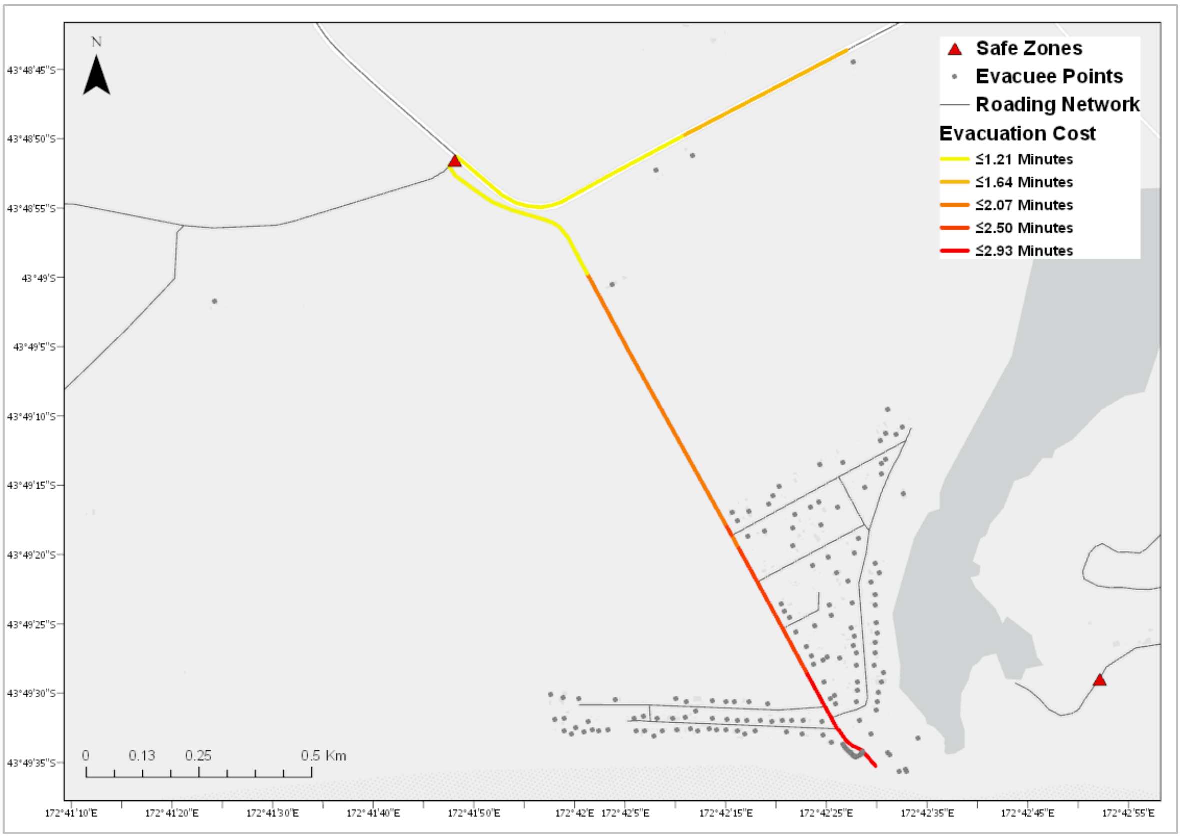

Figure 7.82: Evacuation cost results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

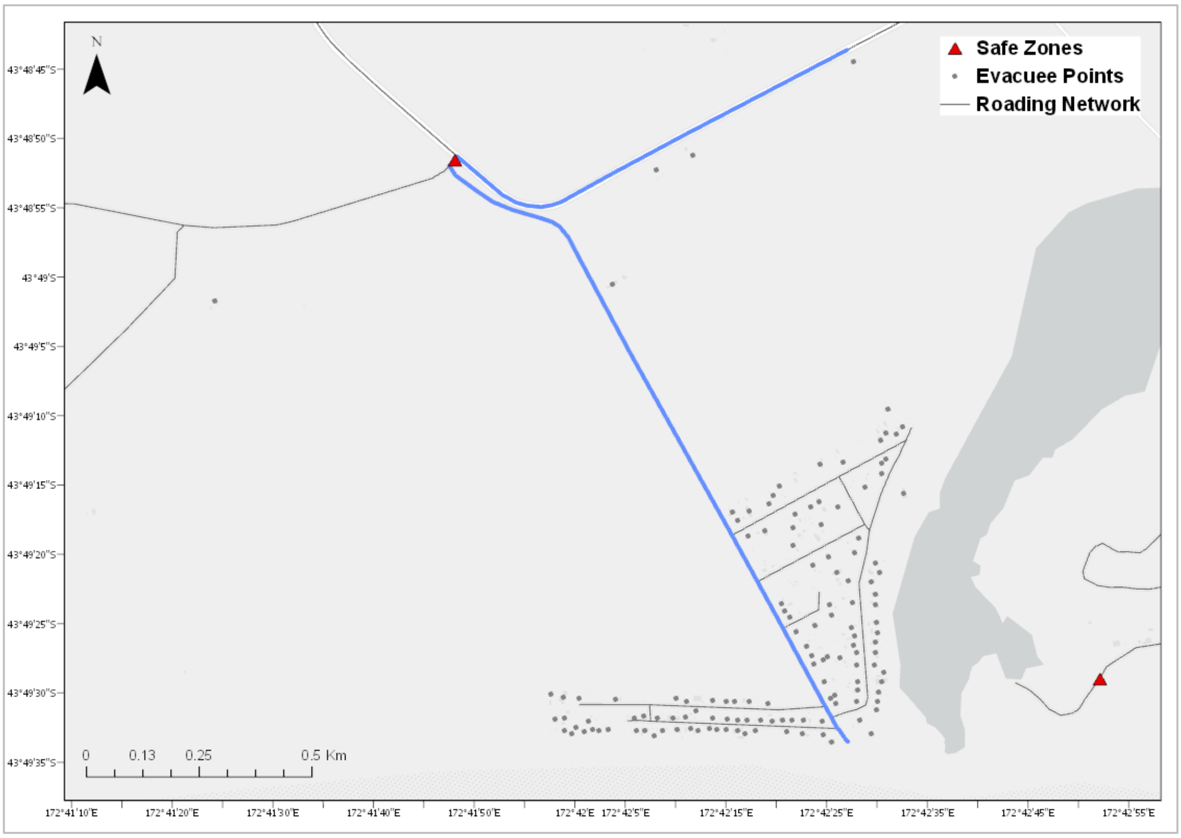

Figure 7.83: Safe zone distribution results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

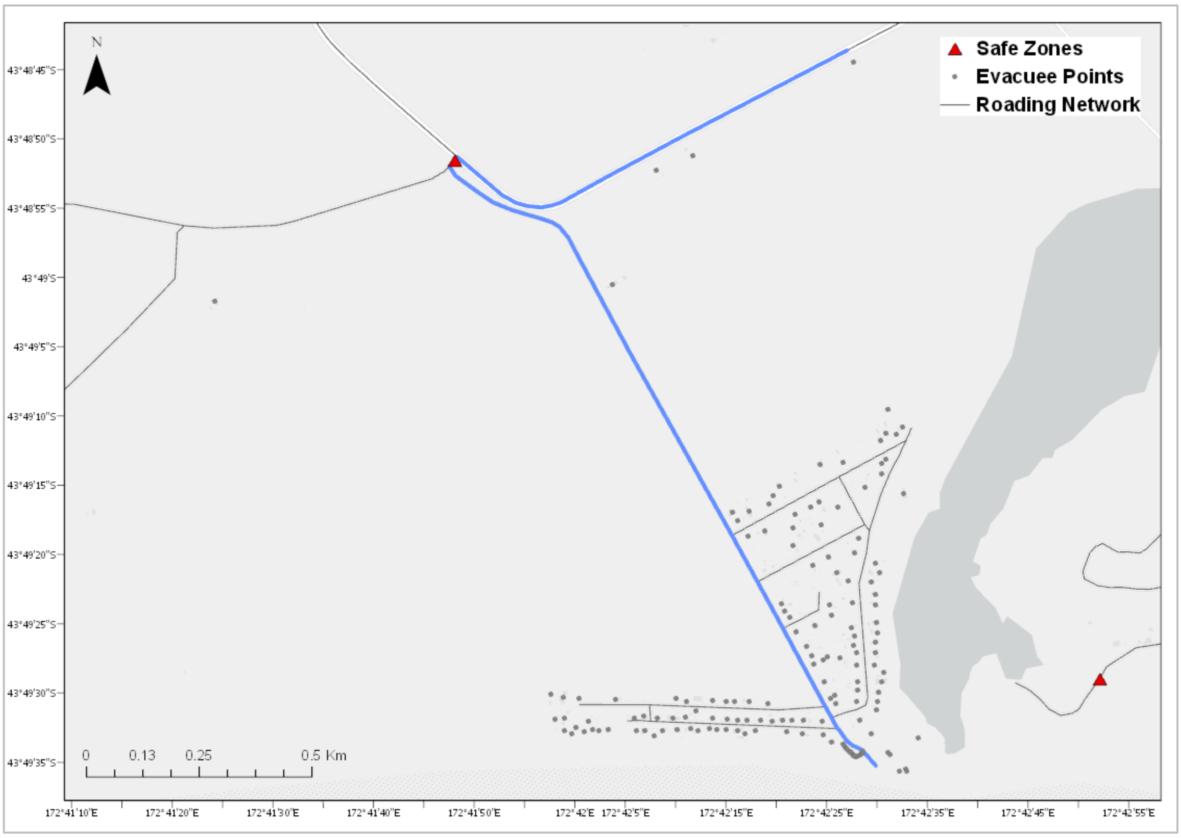

Figure 7.84: Safe zone distribution results for Birdlings Flat – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

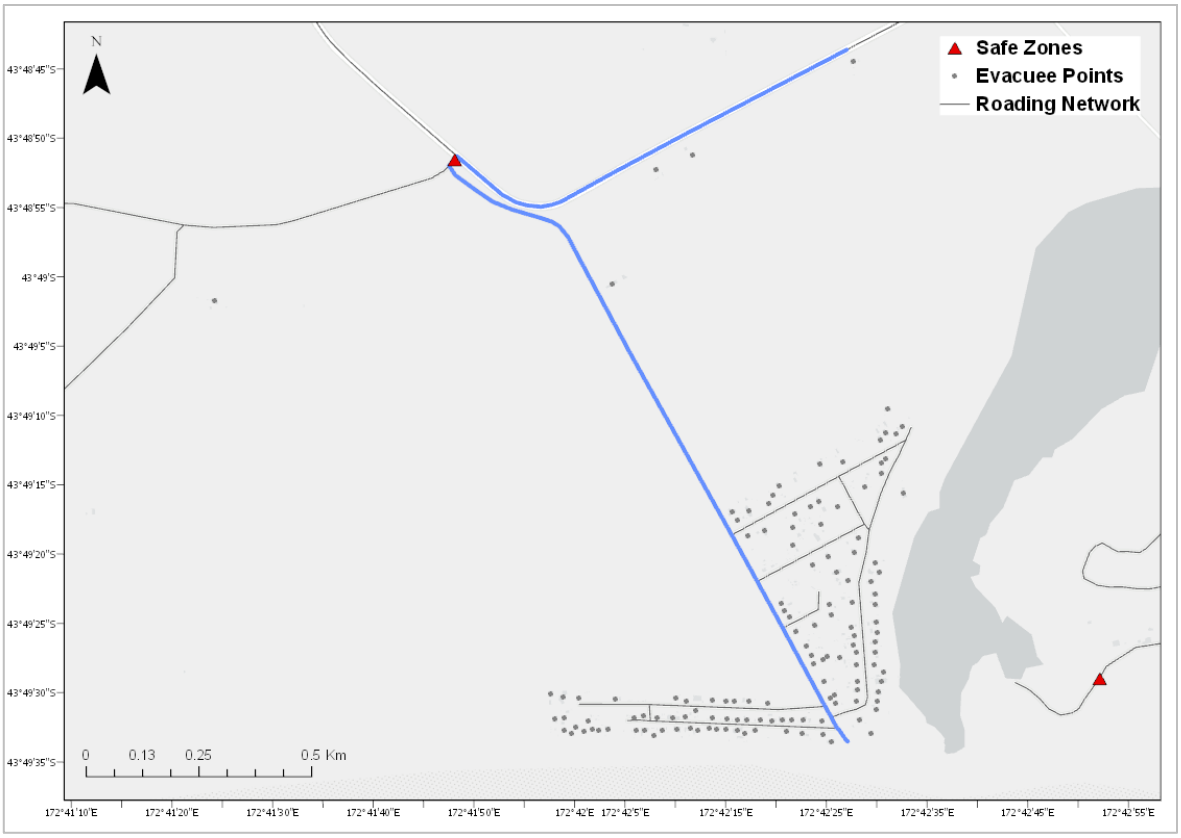

Figure 7.85: Safe zone distribution results for Birdlings Flat – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

c. Cass Bay and Corsair Bay

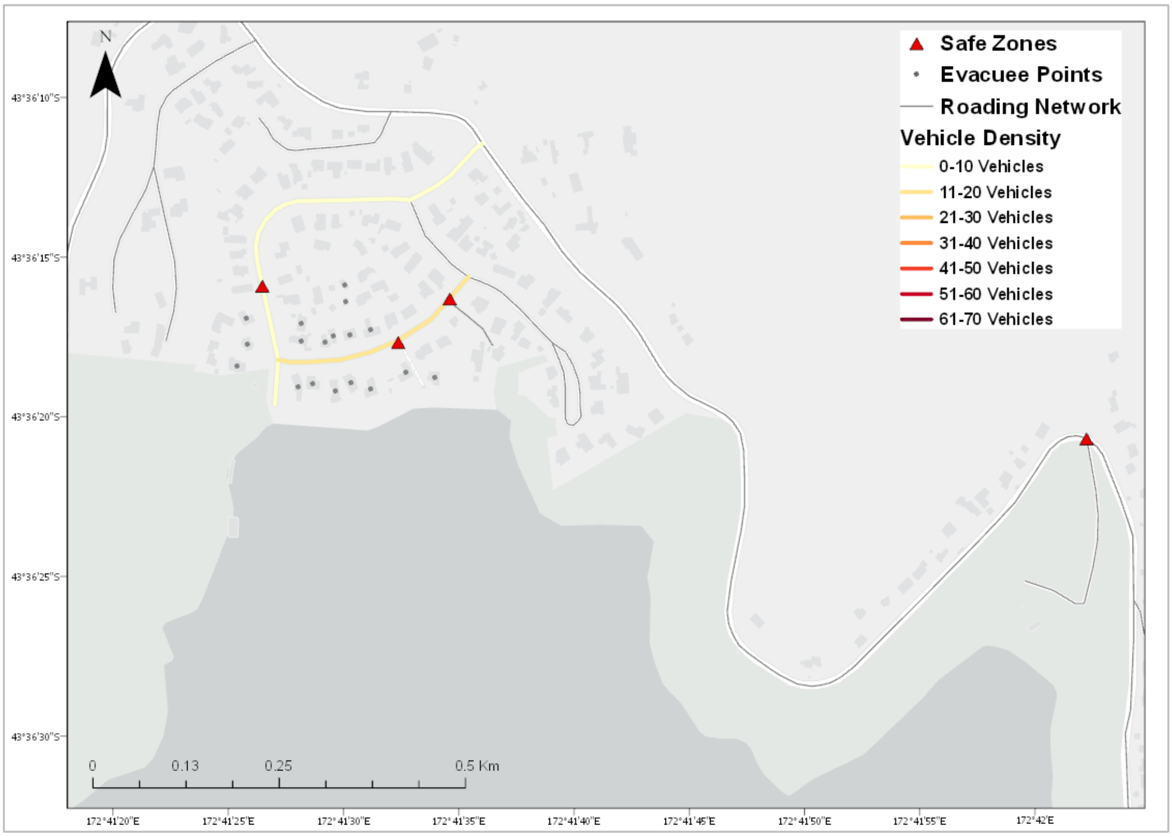

Figure 7.86: Vehicle density count results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

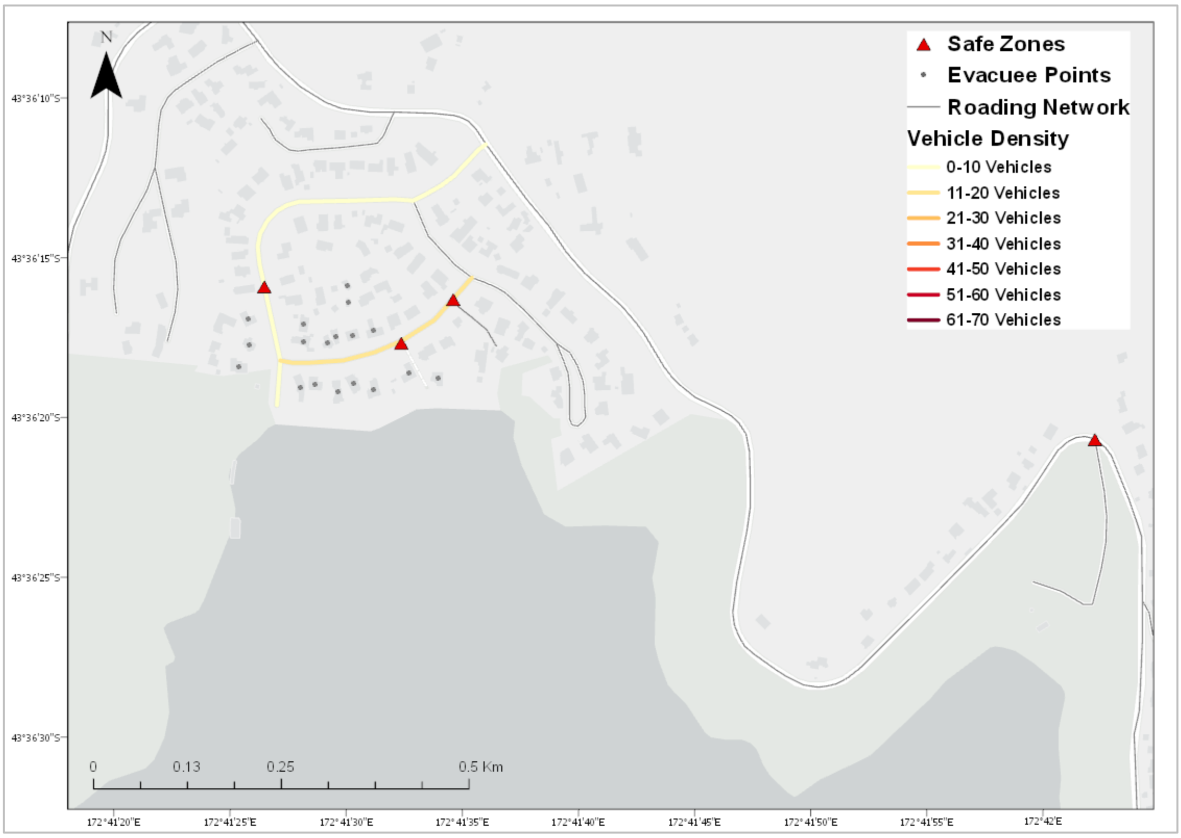

Figure 7.87: Vehicle density count results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

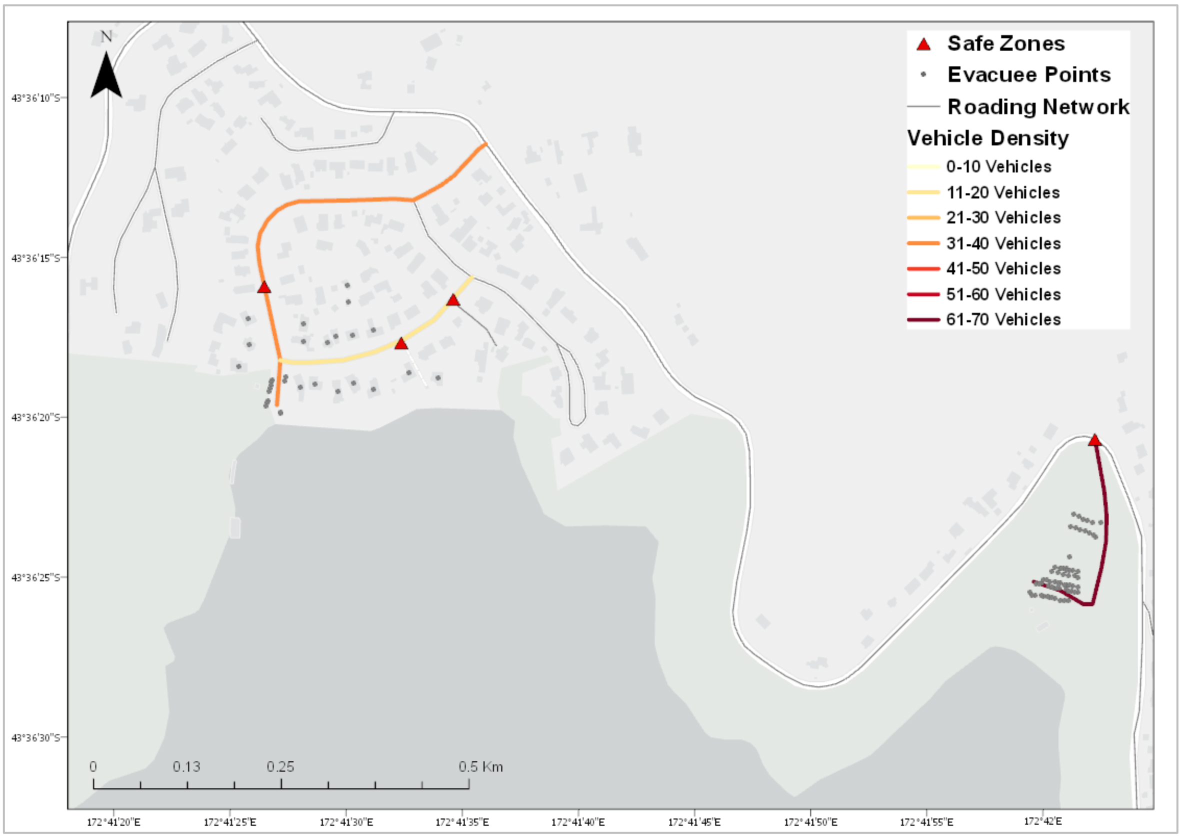

Figure 7.88: Vehicle density count results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

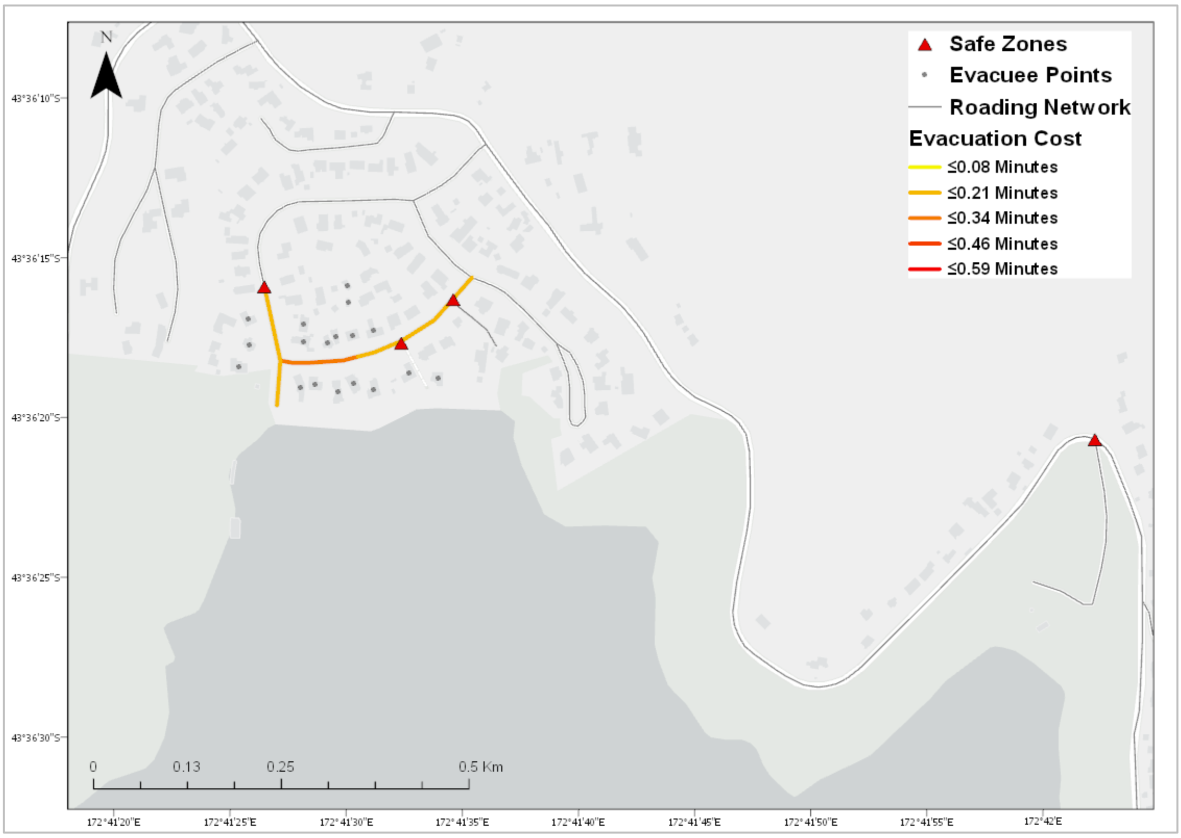

Figure 7.89: Evacuation cost results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

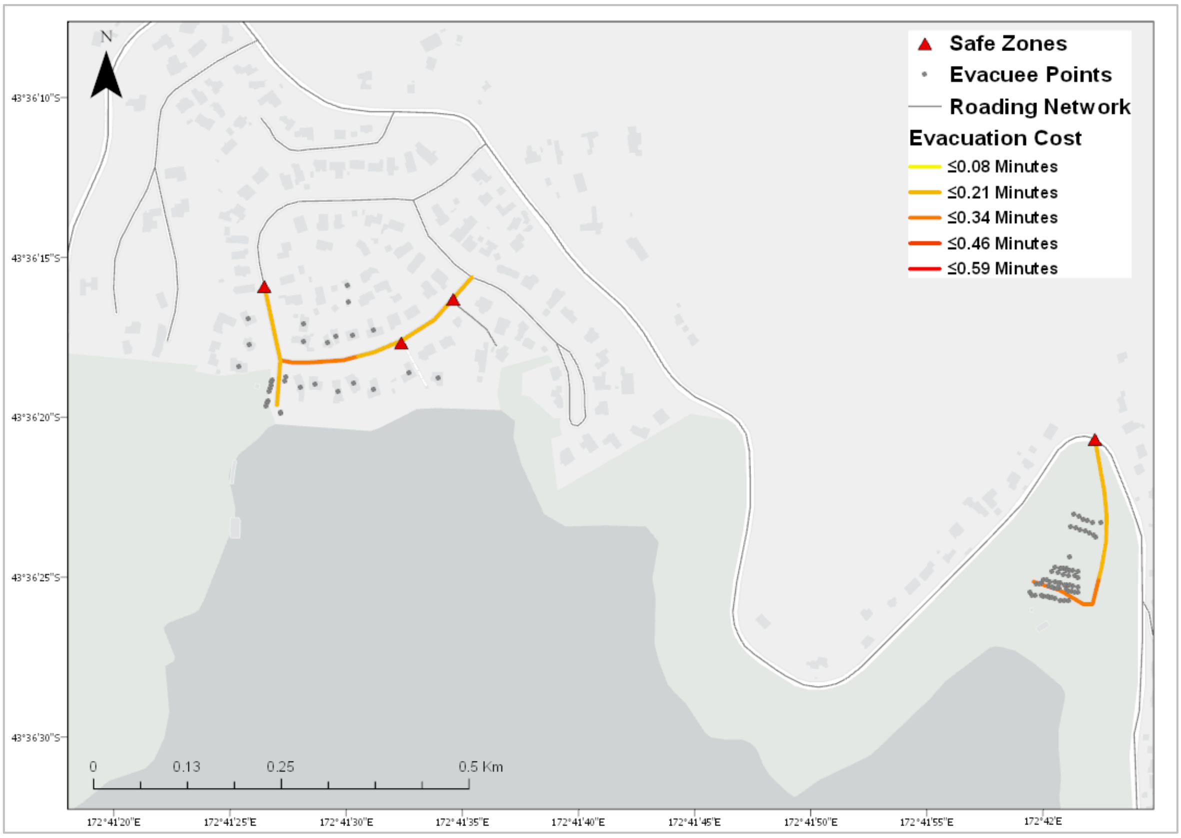

Figure 7.90: Evacuation cost results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

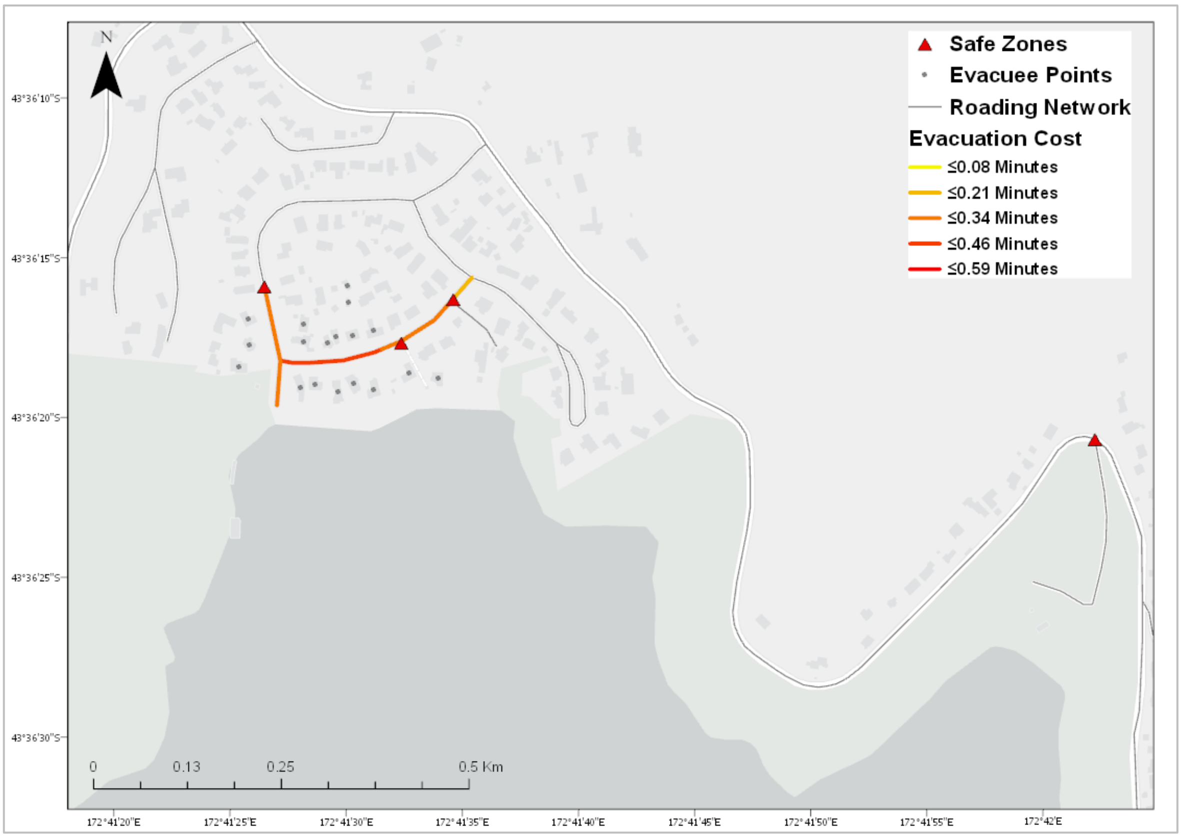

Figure 7.91: Evacuation cost results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

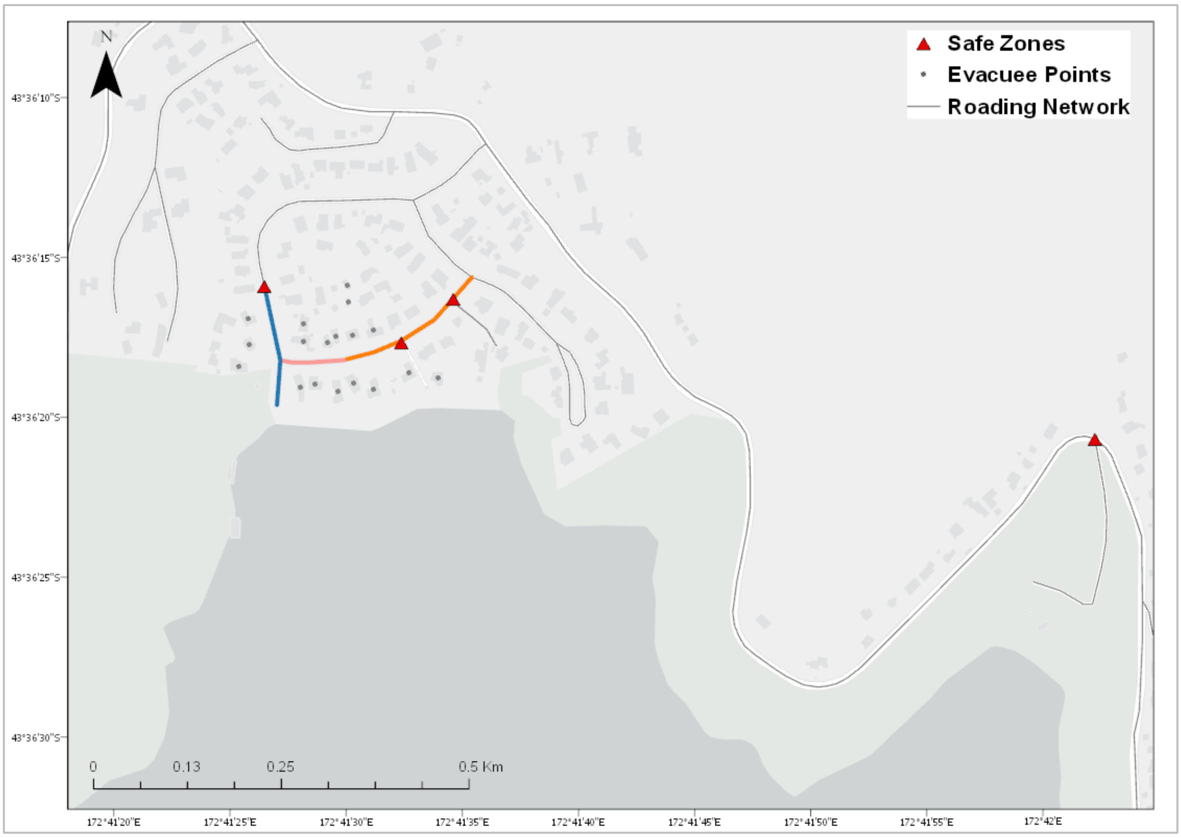

Figure 7.92: Safe zone distribution results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

Figure 7.93: Safe zone distribution results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

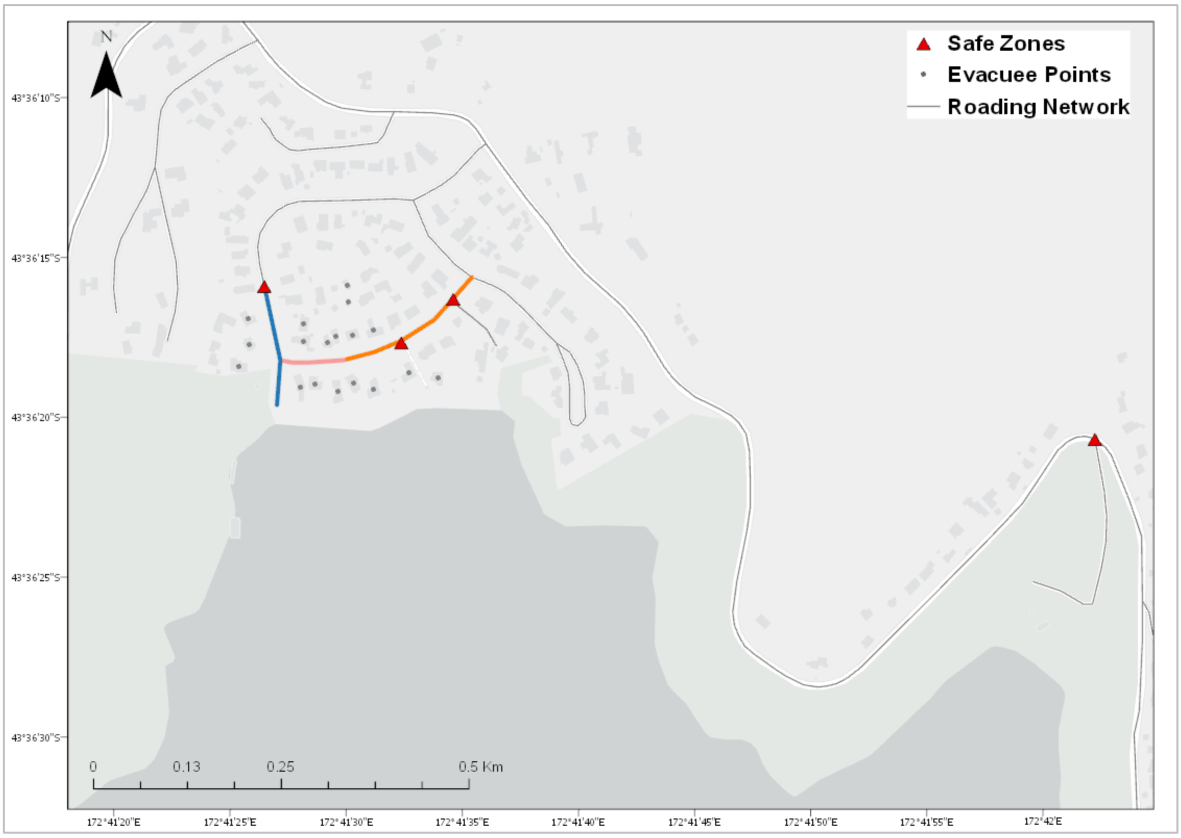

Figure 7.94: Safe zone distribution results for Cass Bay and Corsair Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

d. Duvauchelle

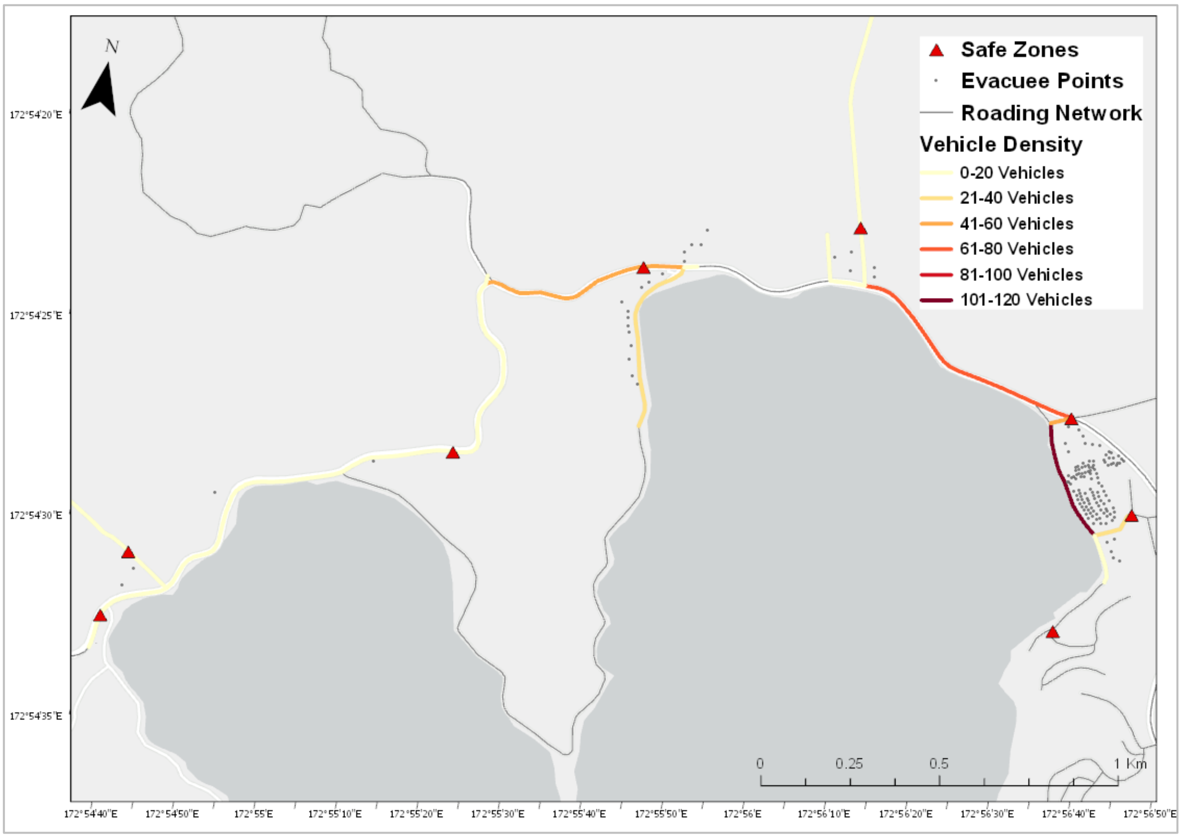

Figure 7.95: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

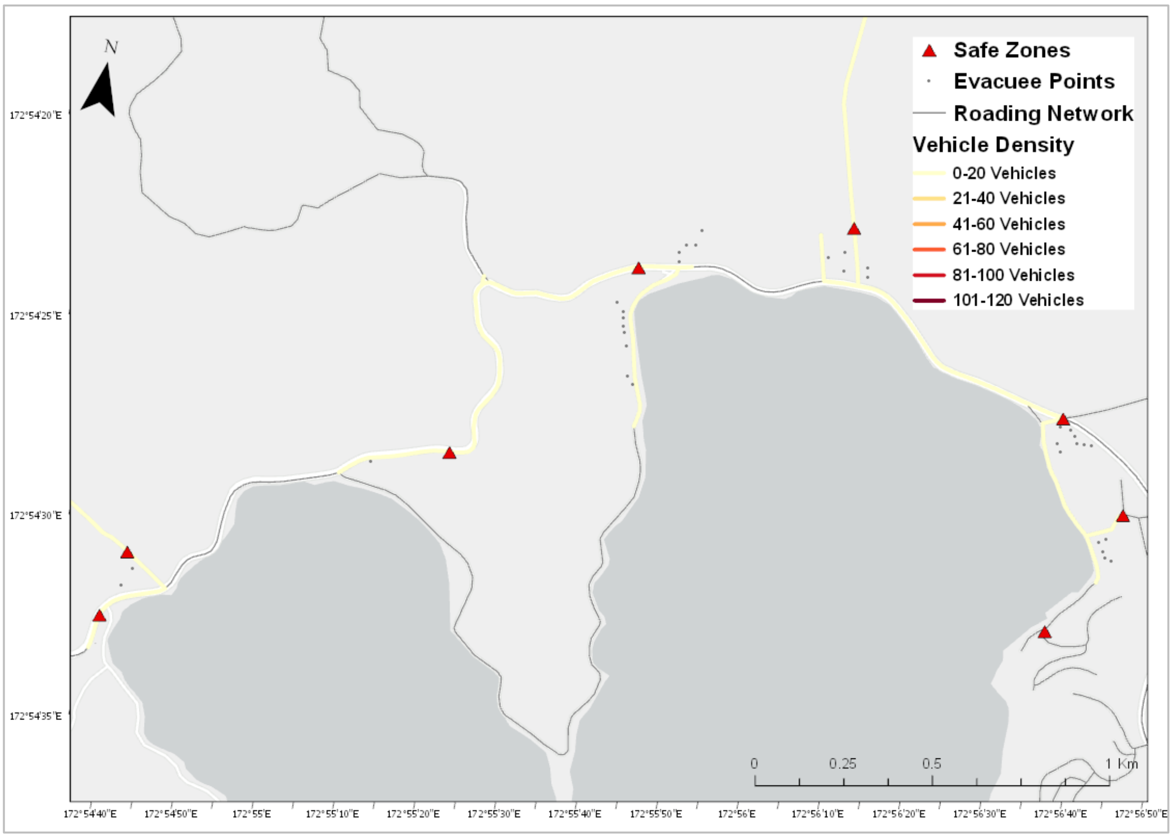

Figure 7.96: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

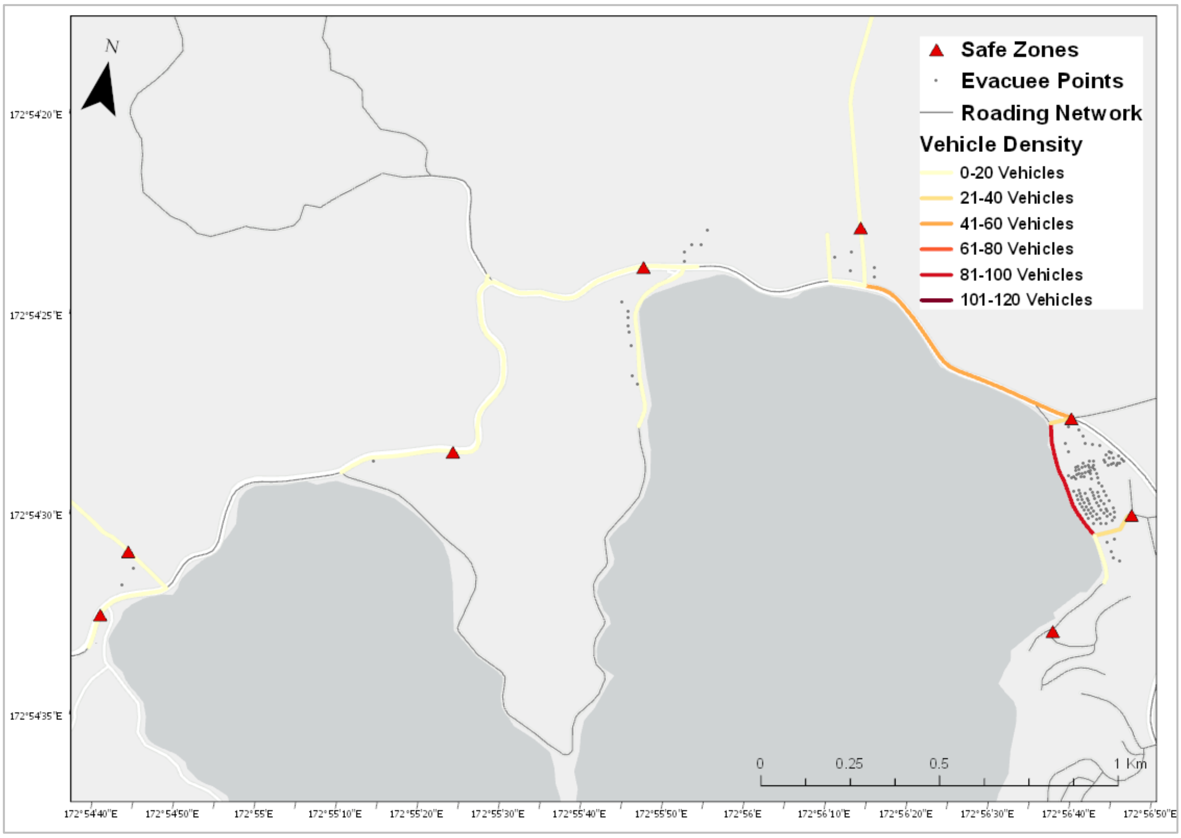

Figure 7.97: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

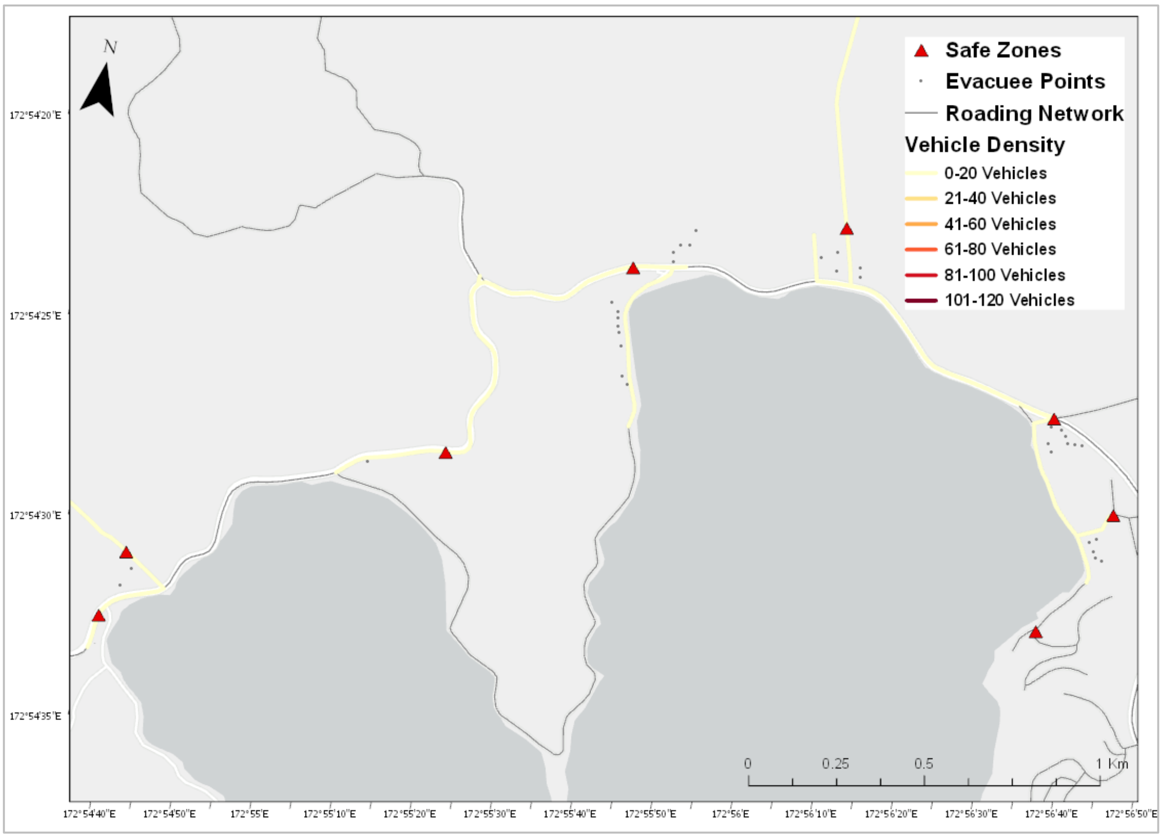

Figure 7.98: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

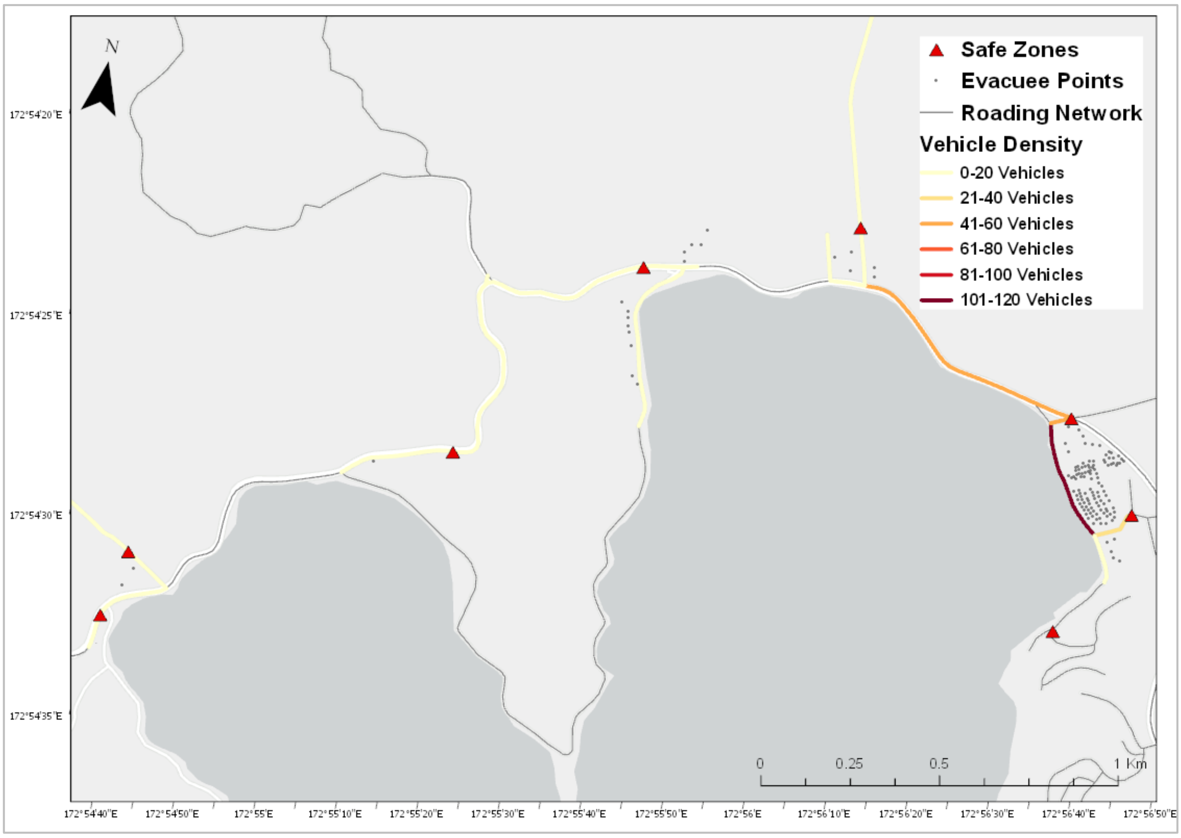

Figure 7.99: Vehicle density count results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

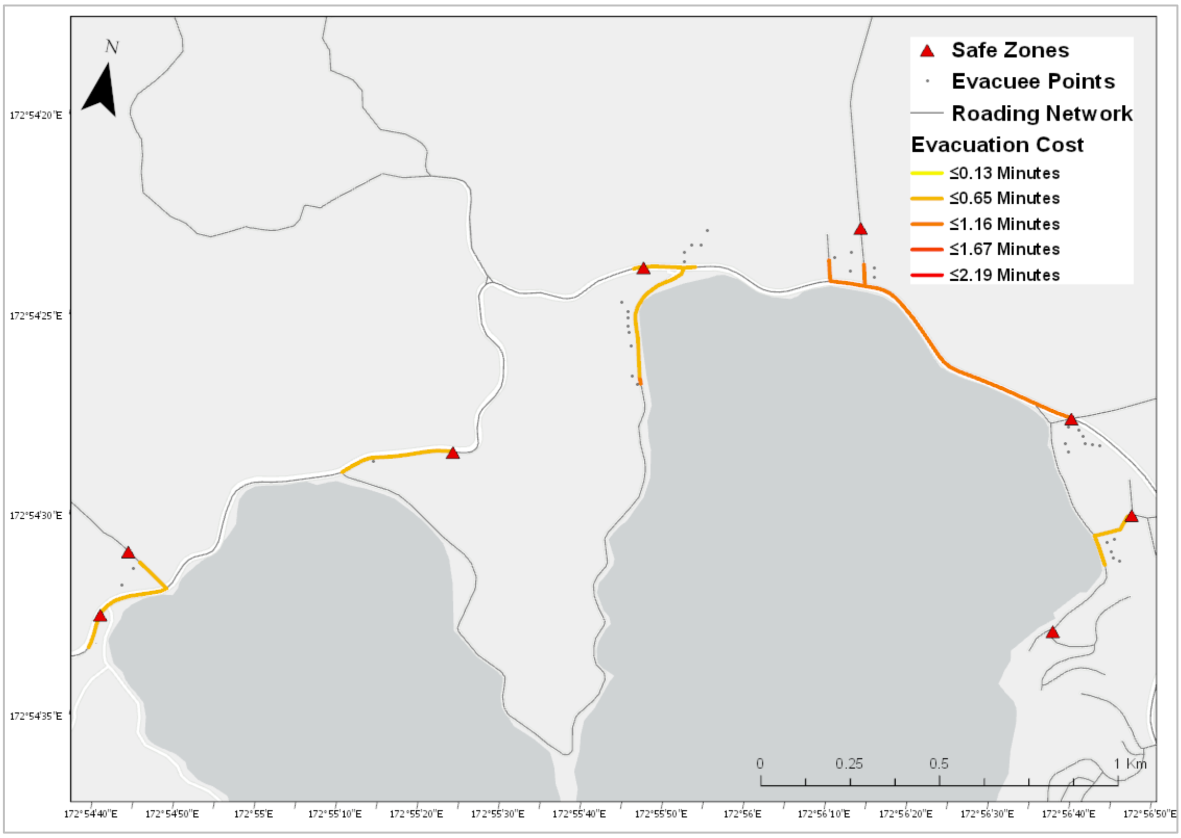

Figure 7.100: Evacuation cost results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

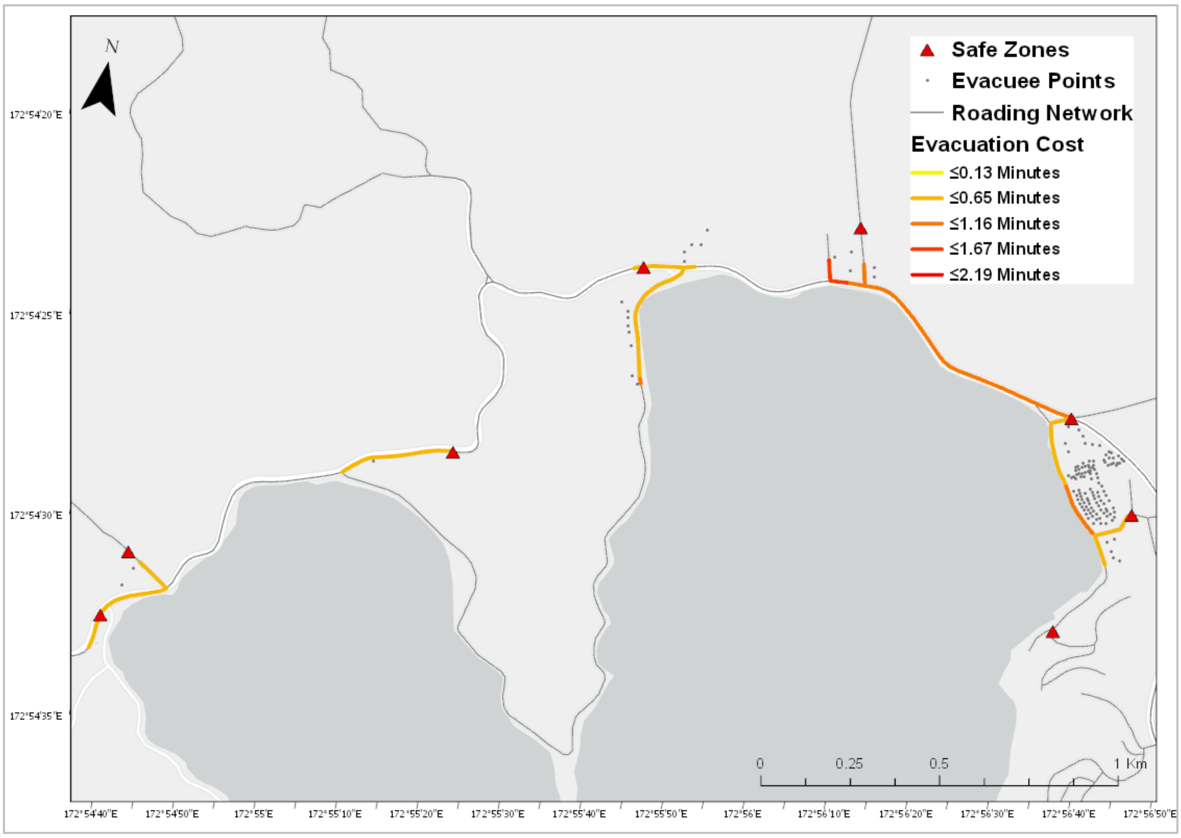

Figure 7.101: Evacuation cost results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

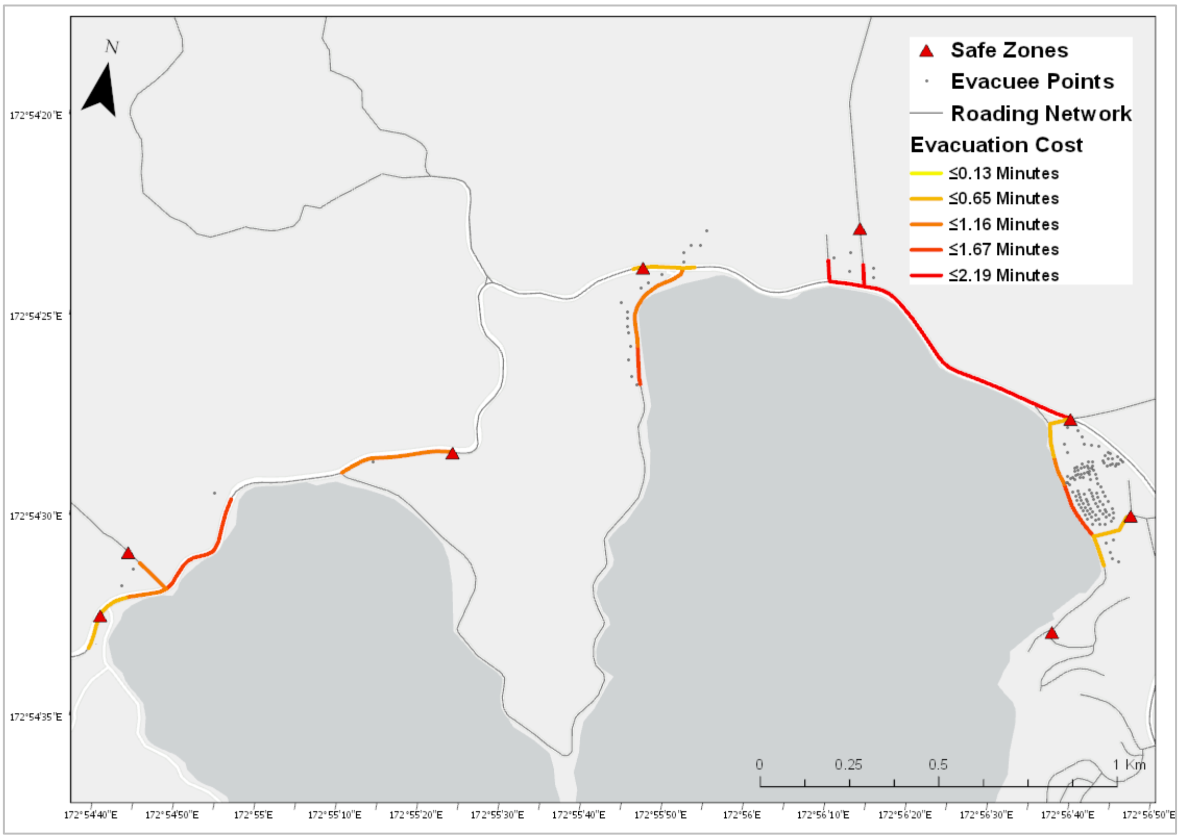

Figure 7.102: Evacuation cost results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

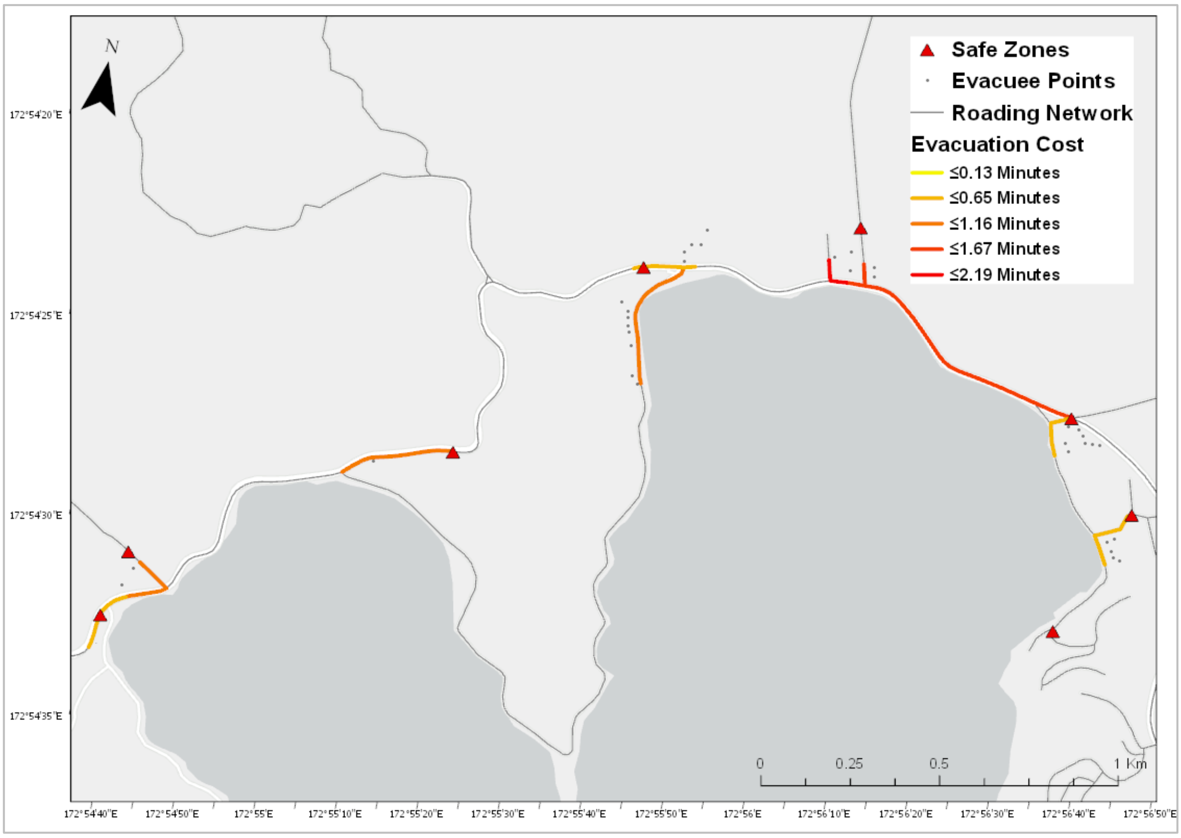

Figure 7.103: Evacuation cost results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

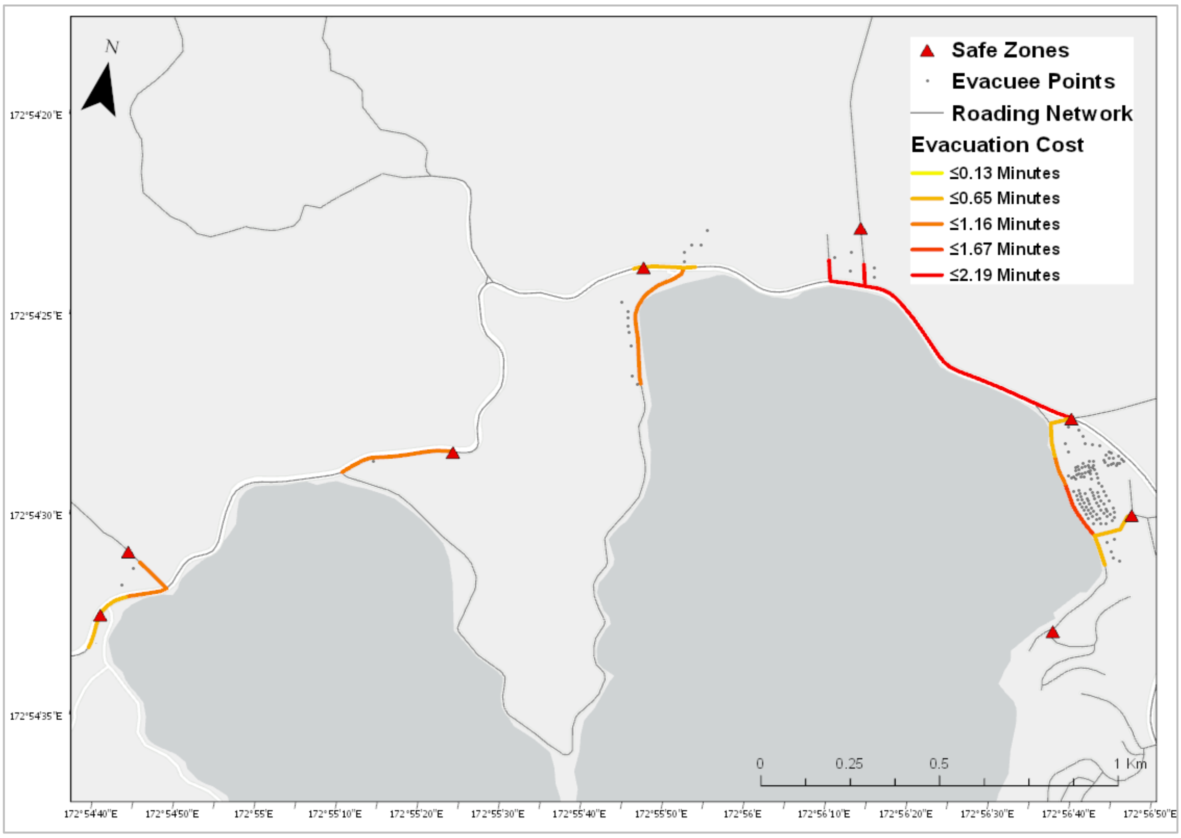

Figure 7.104: Evacuation cost results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

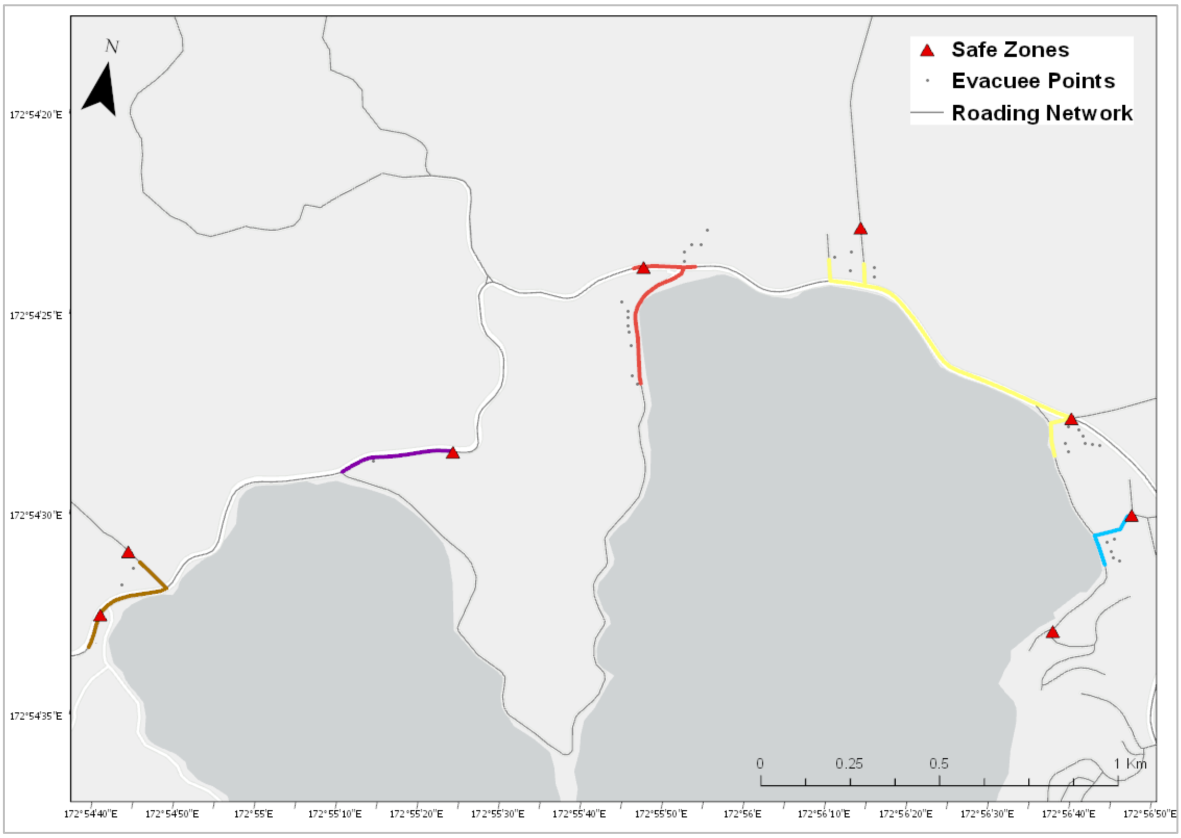

Figure 7.105: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

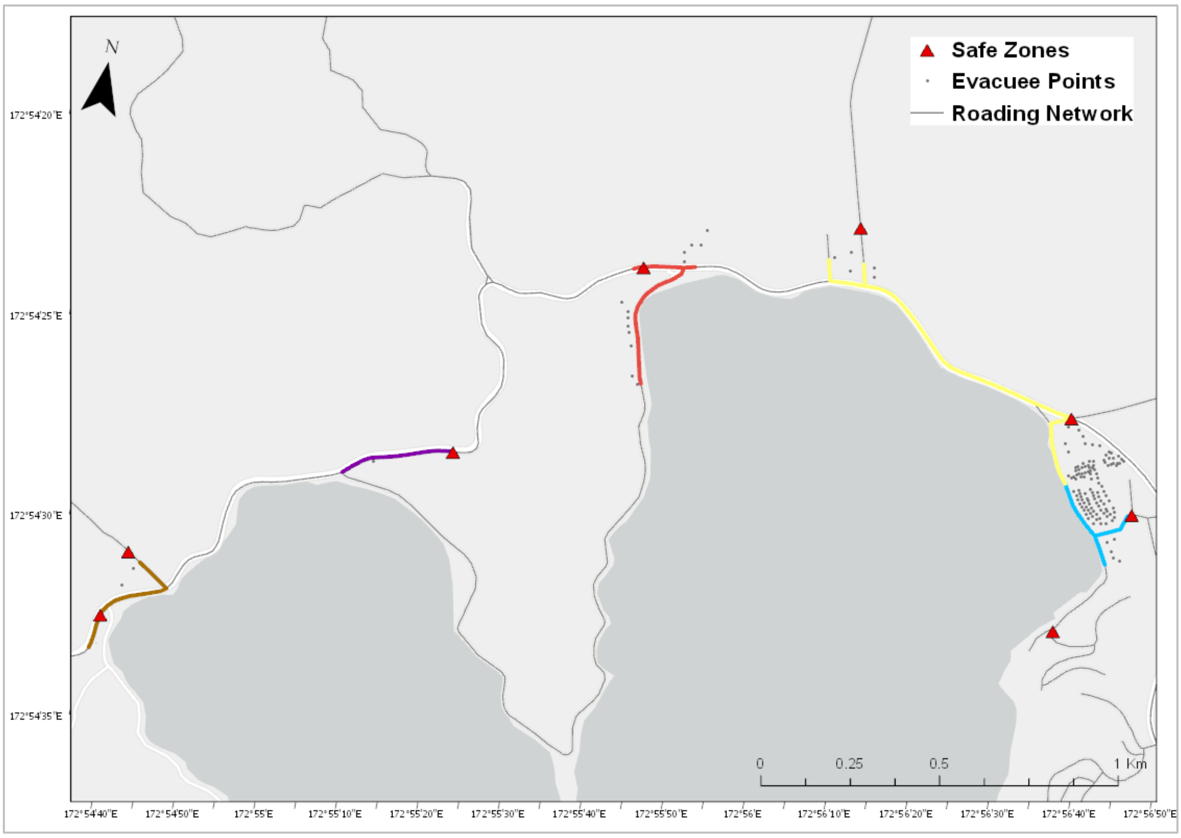

Figure 7.106: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

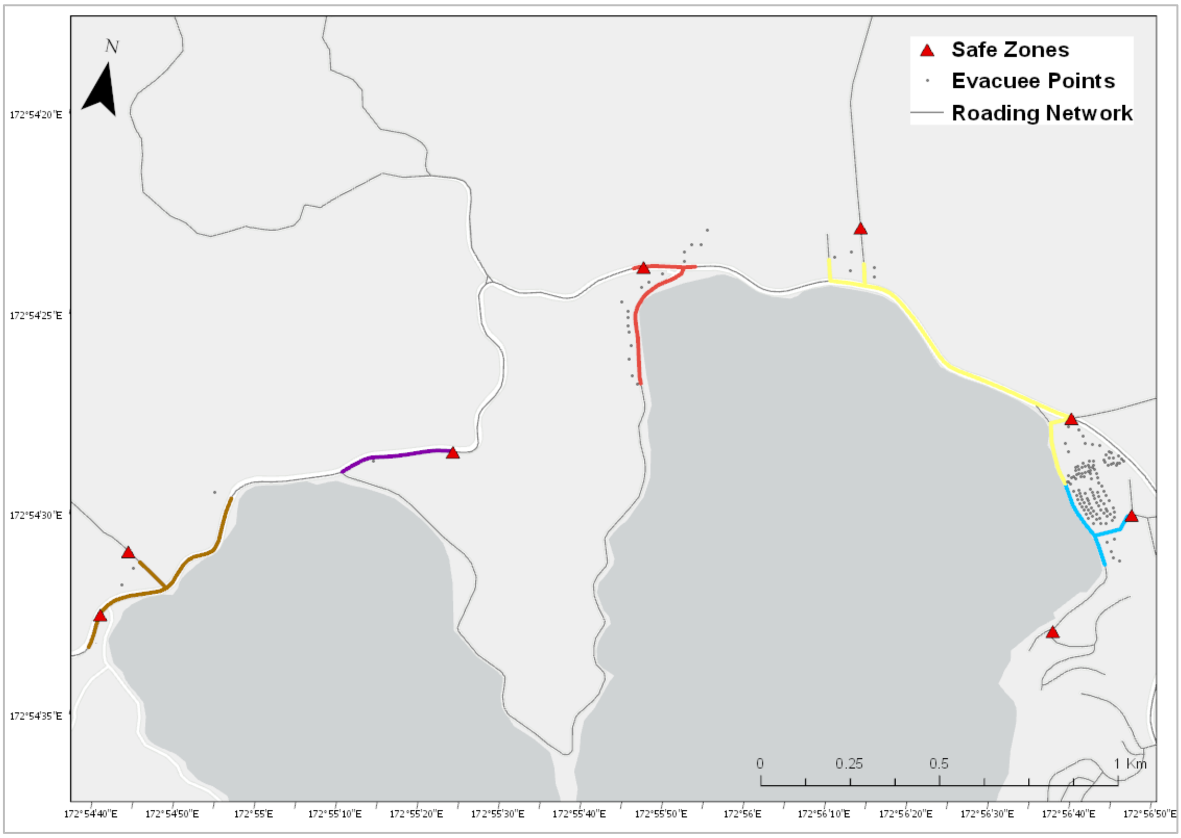

Figure 7.107: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

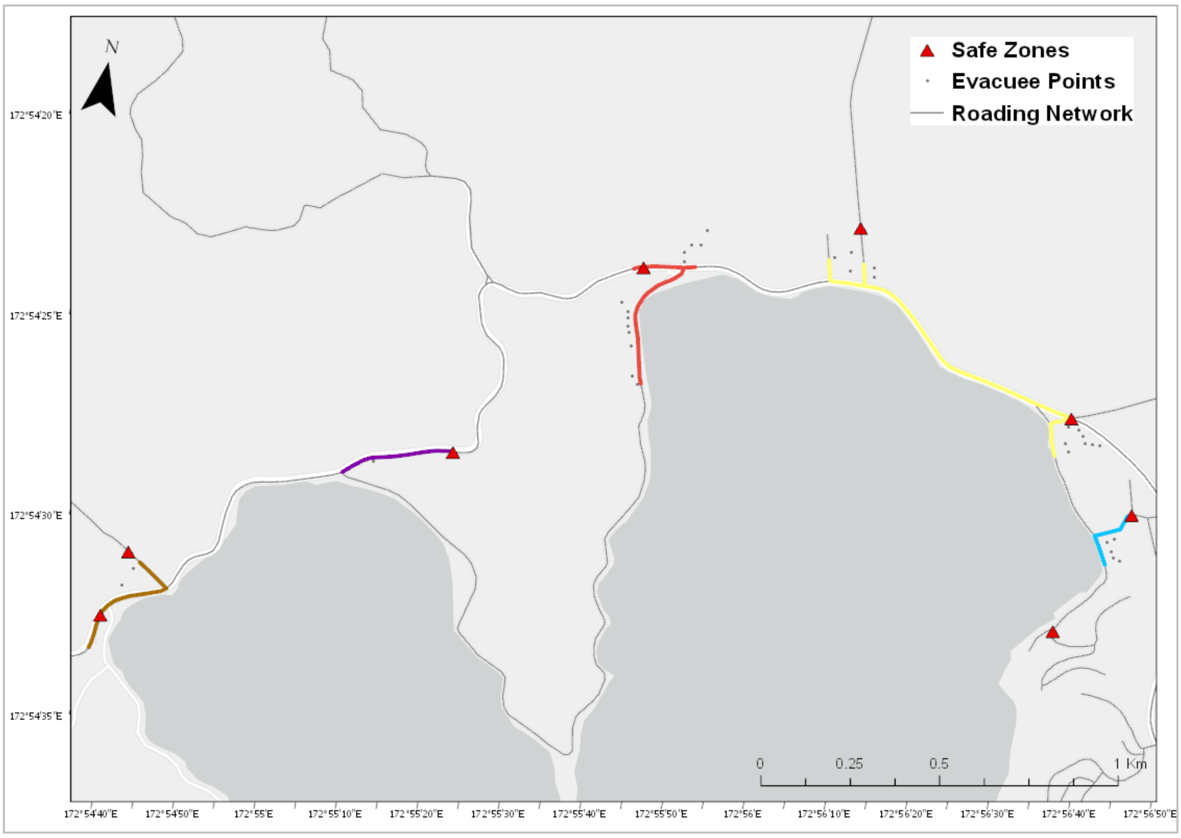

Figure 7.108: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

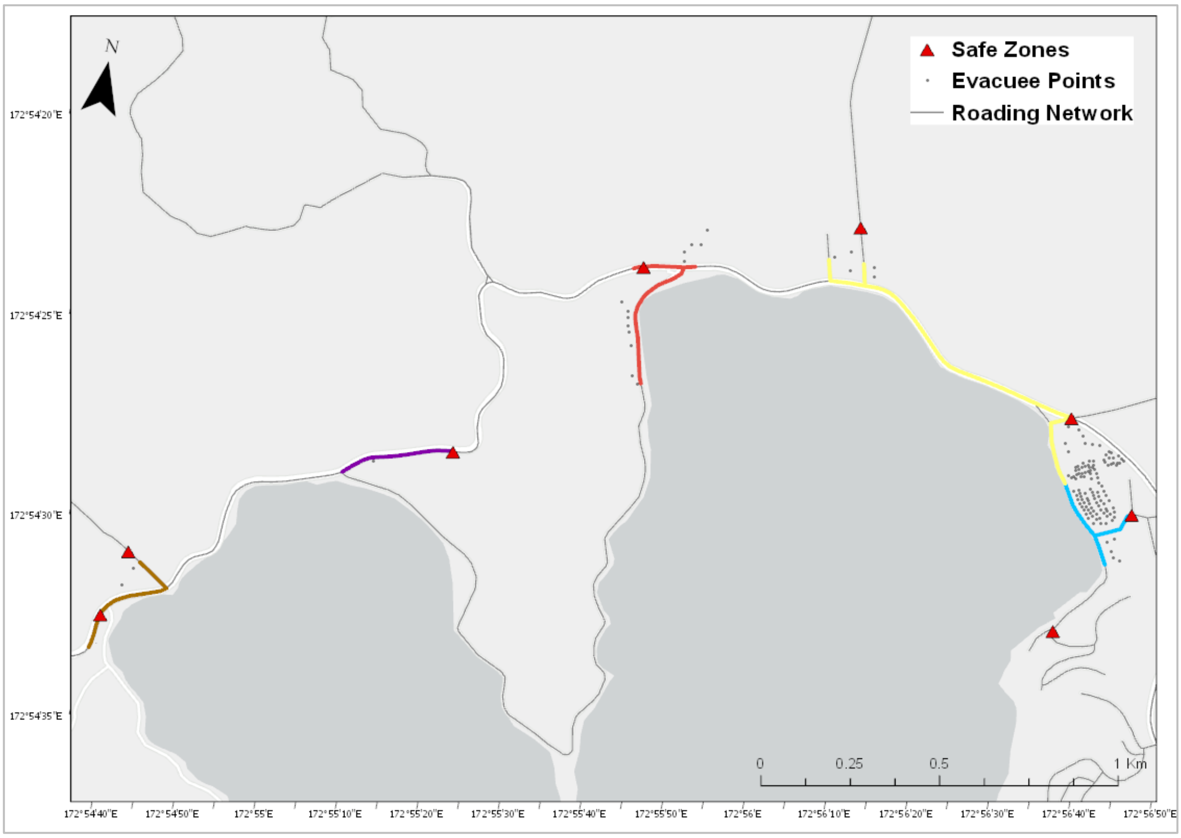

Figure 7.109: Safe zone distribution results for Duvauchelle – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

e. Little Akaloa

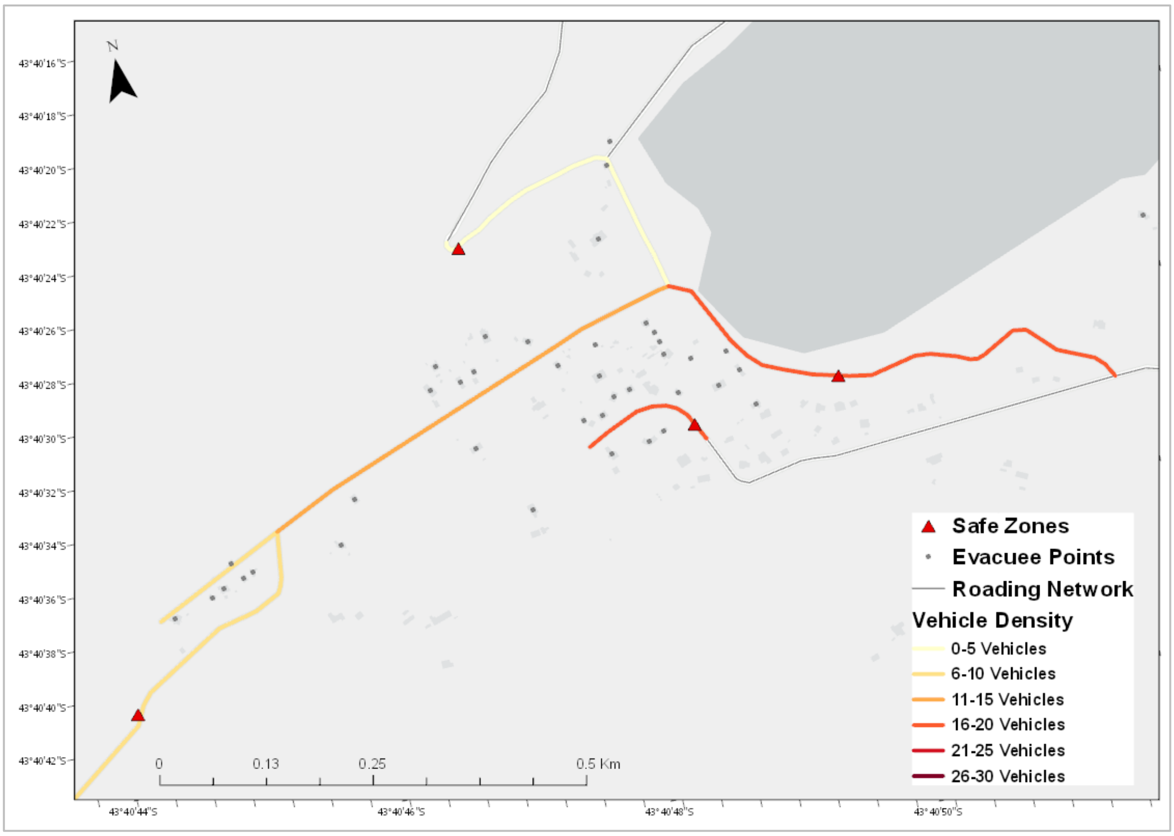

Figure 7.110: Vehicle density count results for Little Akaloa– modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

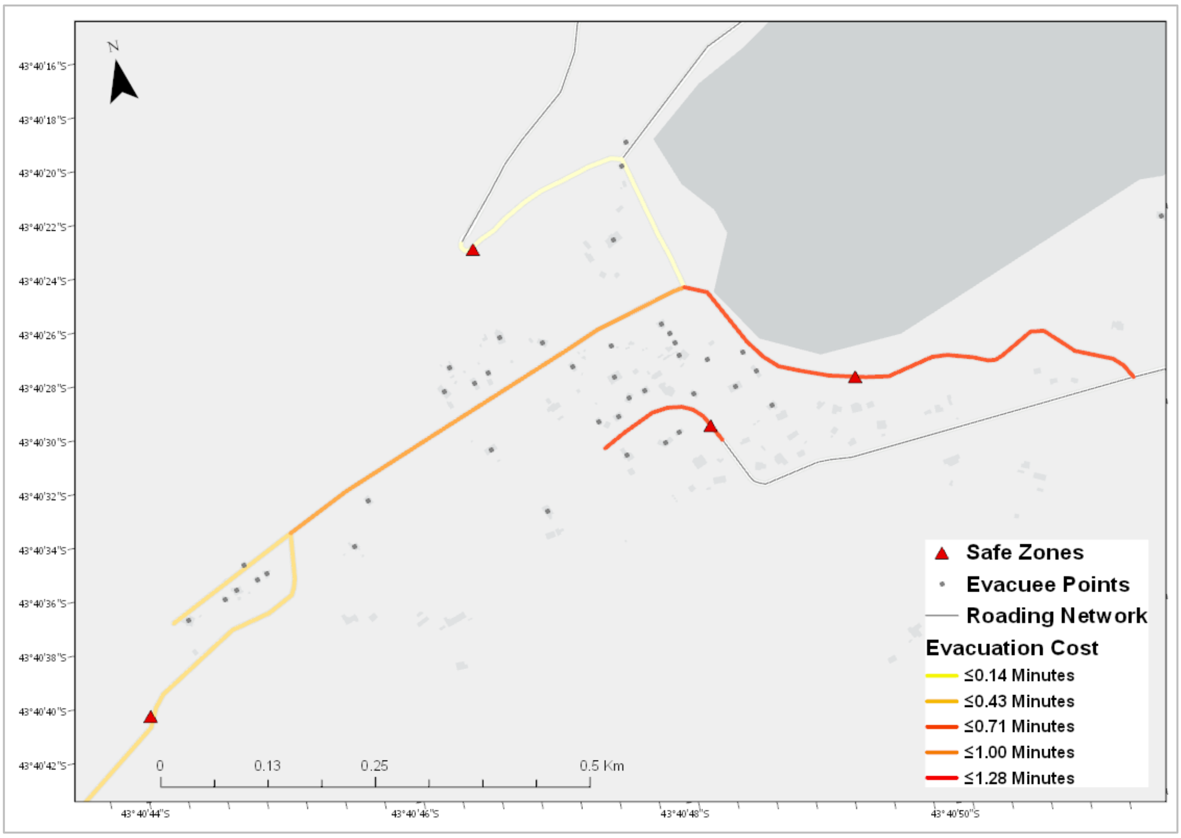

Figure 7.111: Vehicle density count results for Little Akaloa– modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

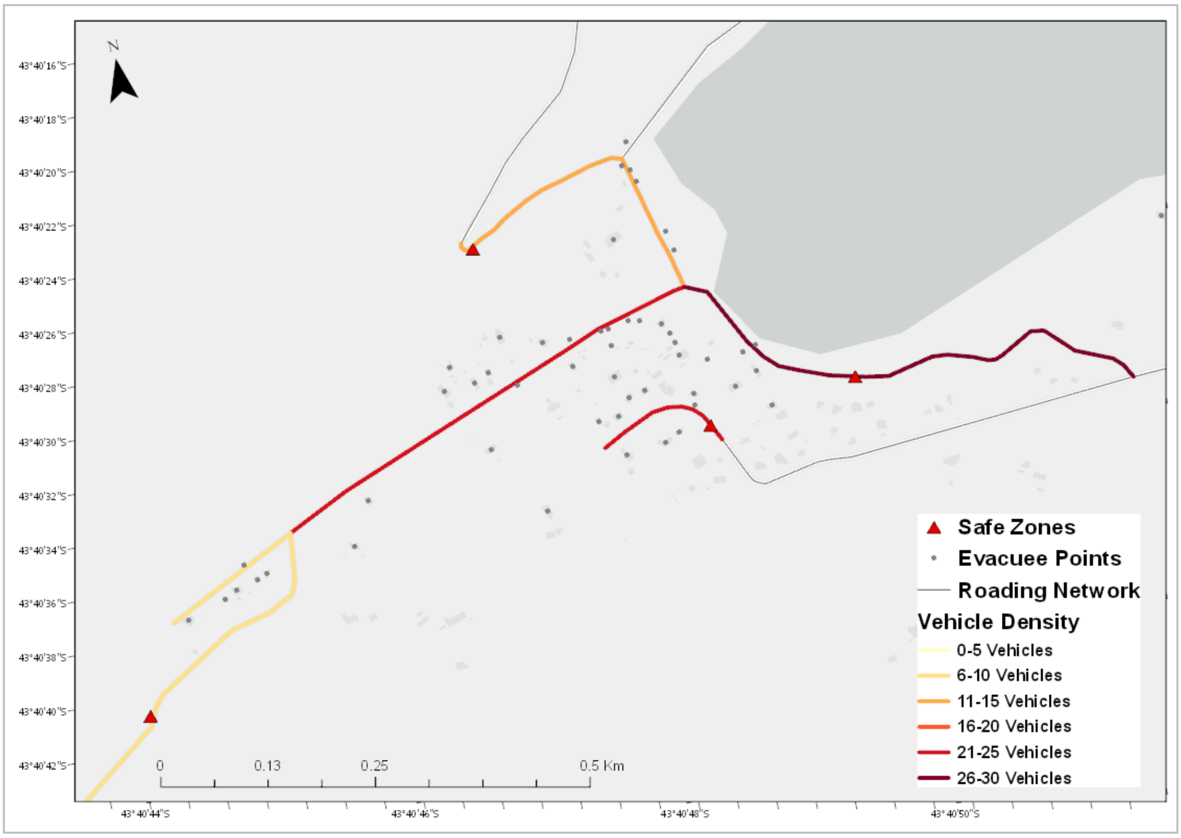

Figure 7.112: Vehicle density count results for Little Akaloa – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario

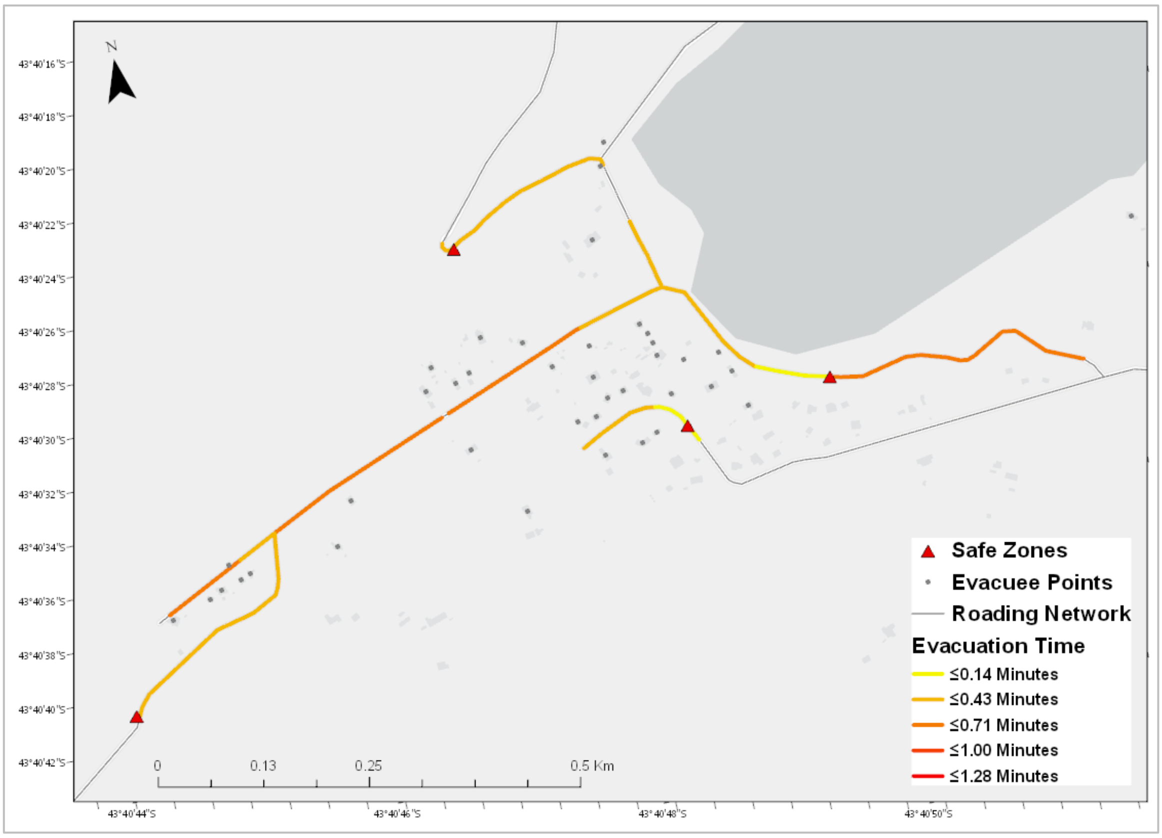

Figure 7.113: Evacuation cost results for Little Akaloa – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

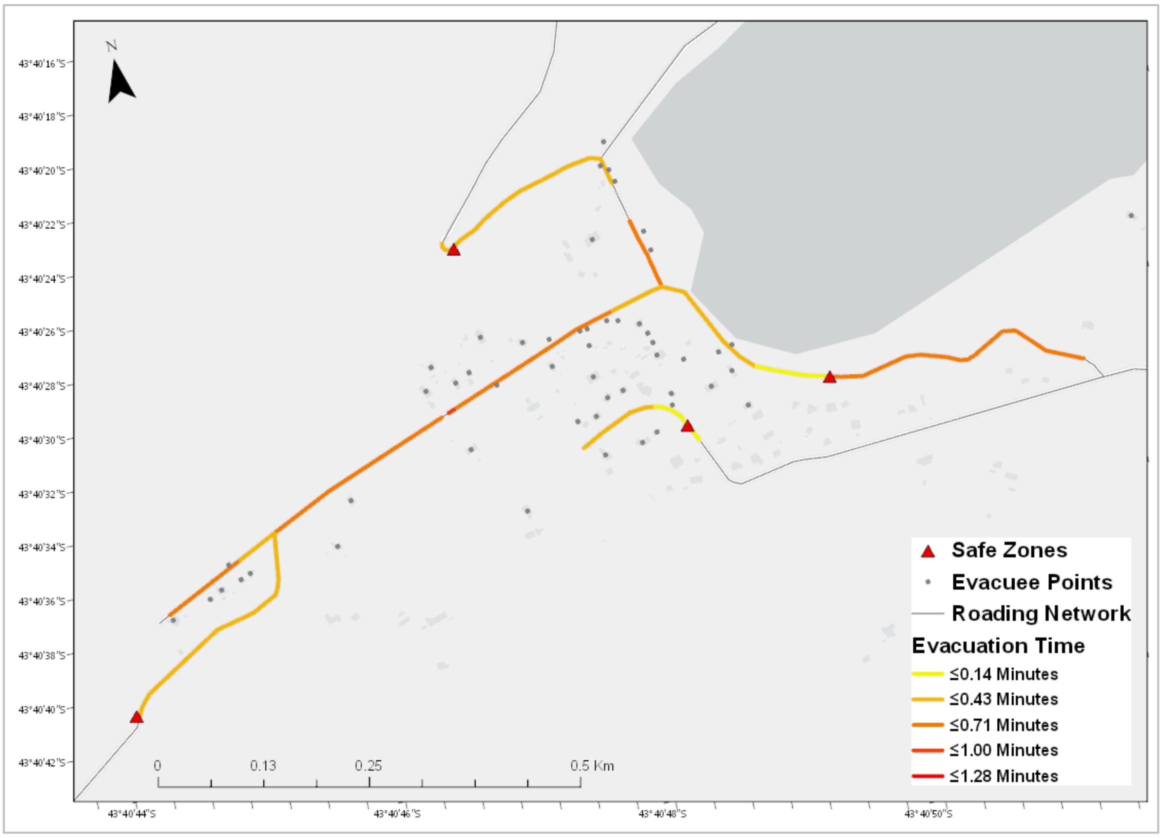

Figure 7.114: Evacuation cost results for Little Akaloa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

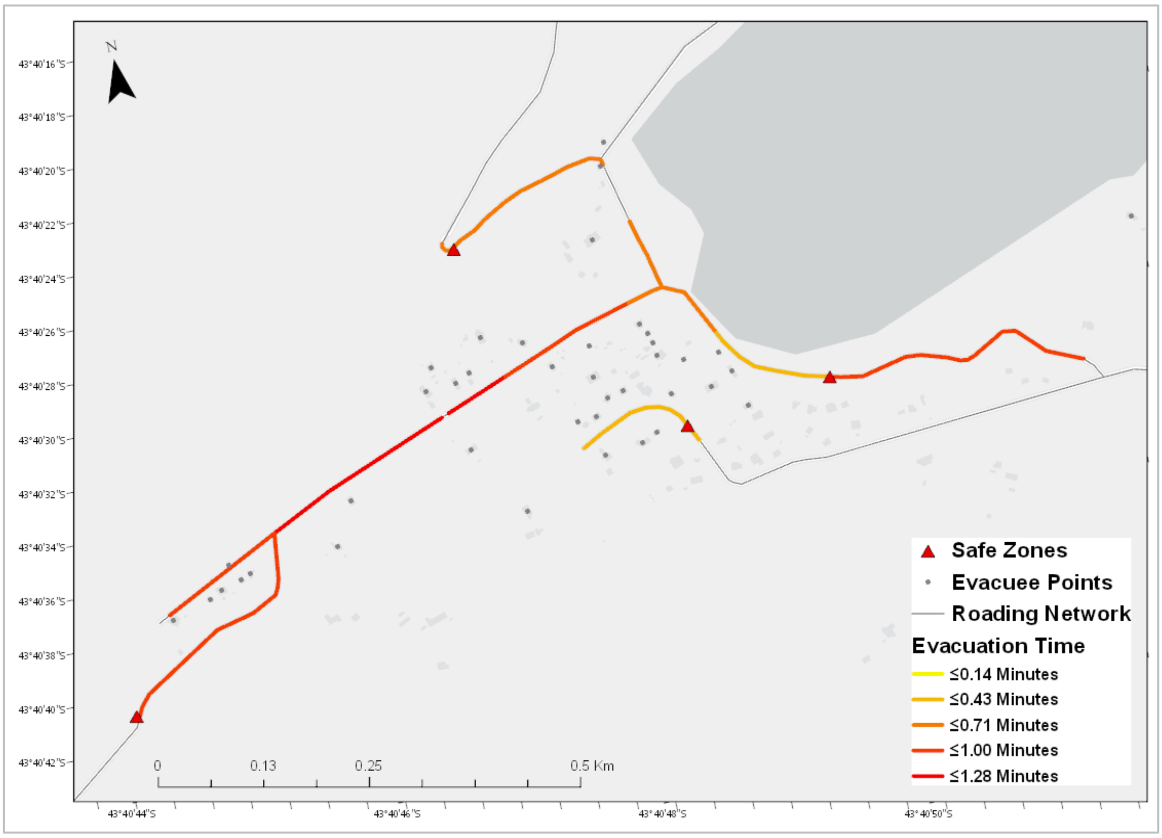

Figure 7.115: Evacuation cost results for Little Akaloa – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

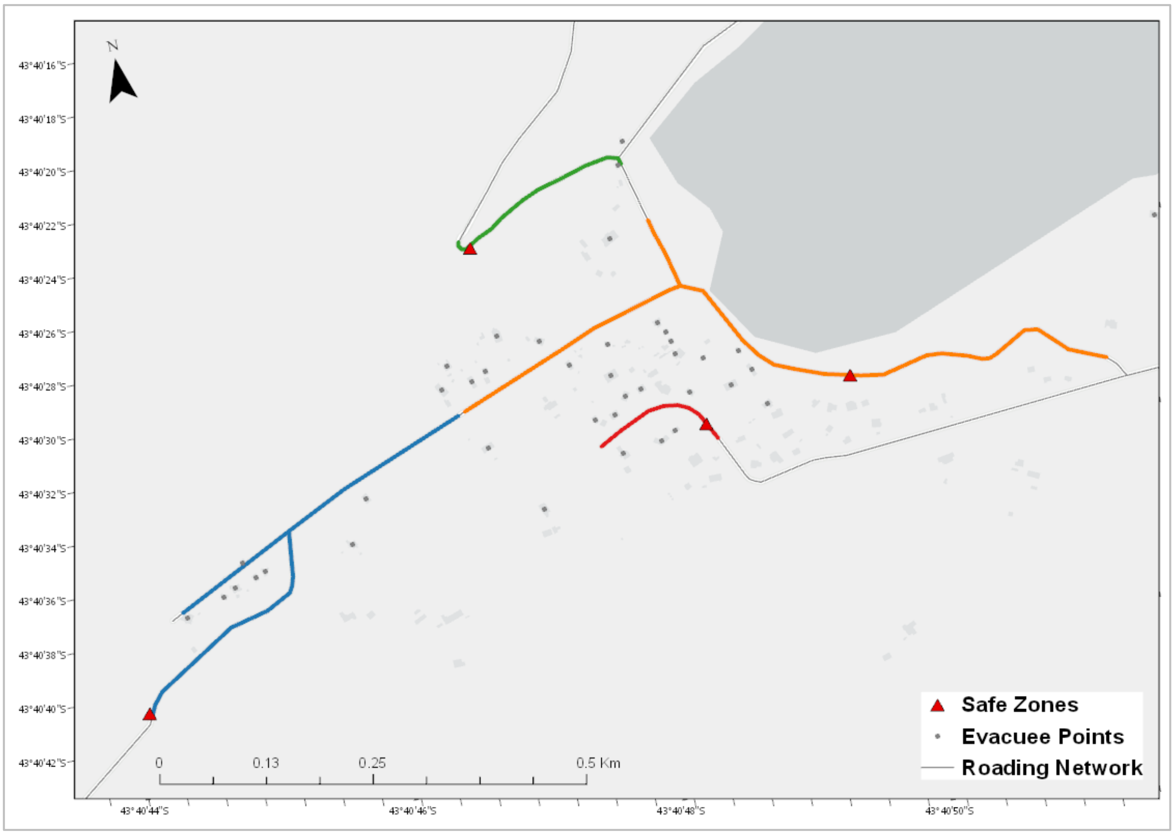

Figure 7.116: Safe zone distribution results for Little Akaloa – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

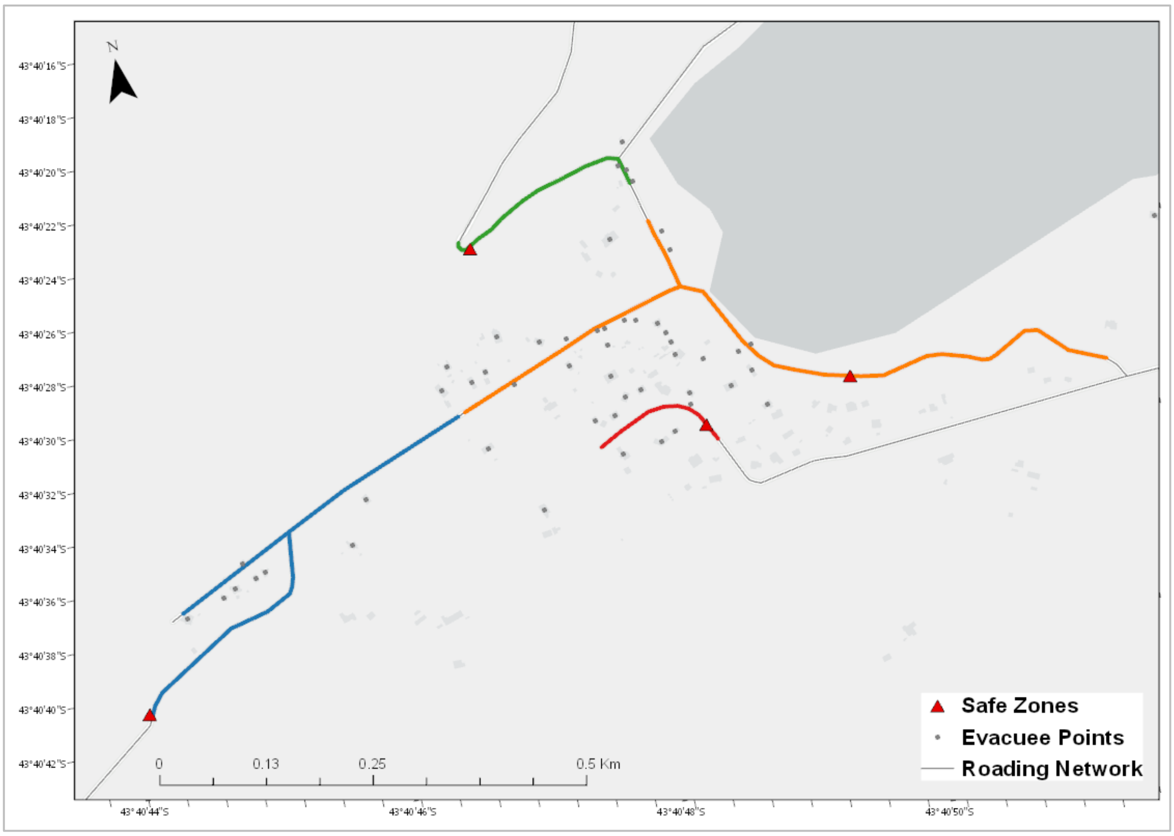

Figure 7.117: Safe zone distribution results for Little Akaloa – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

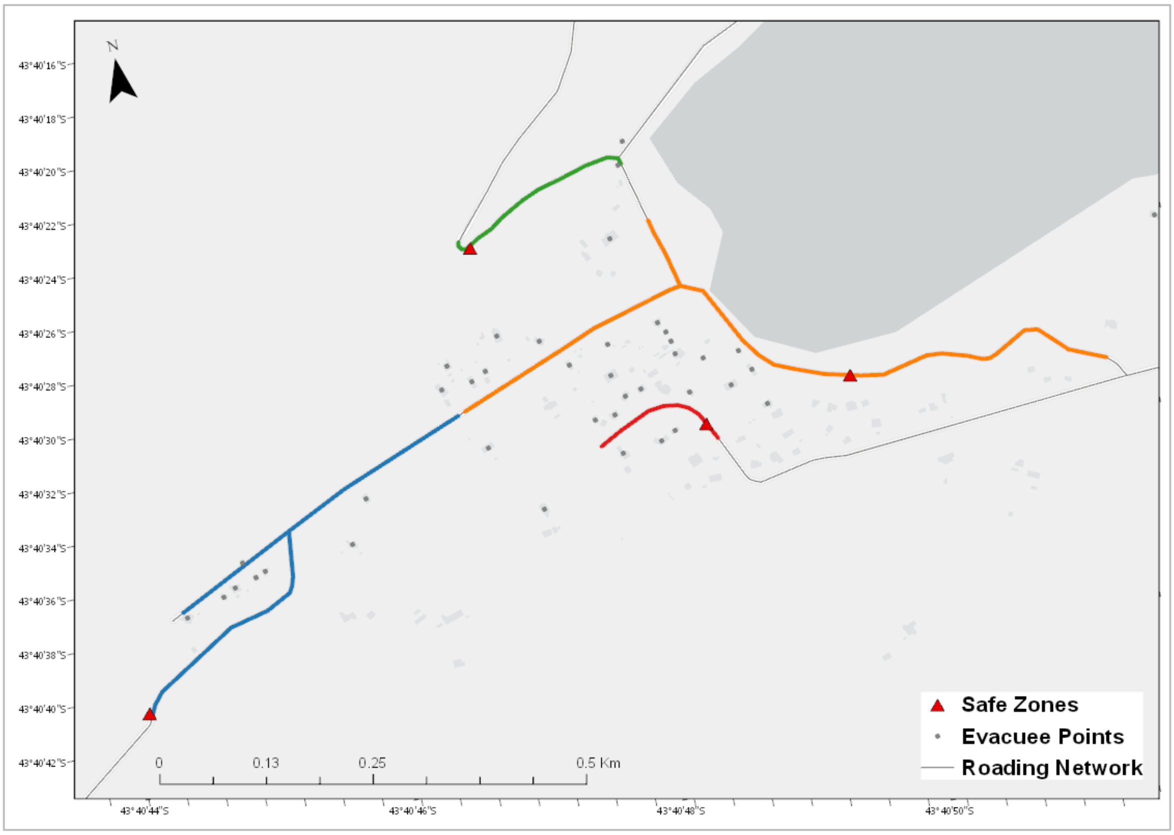

Figure 7.118: Safe zone distribution results for Little Akaloa – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

iv. Reduced Safe Zones

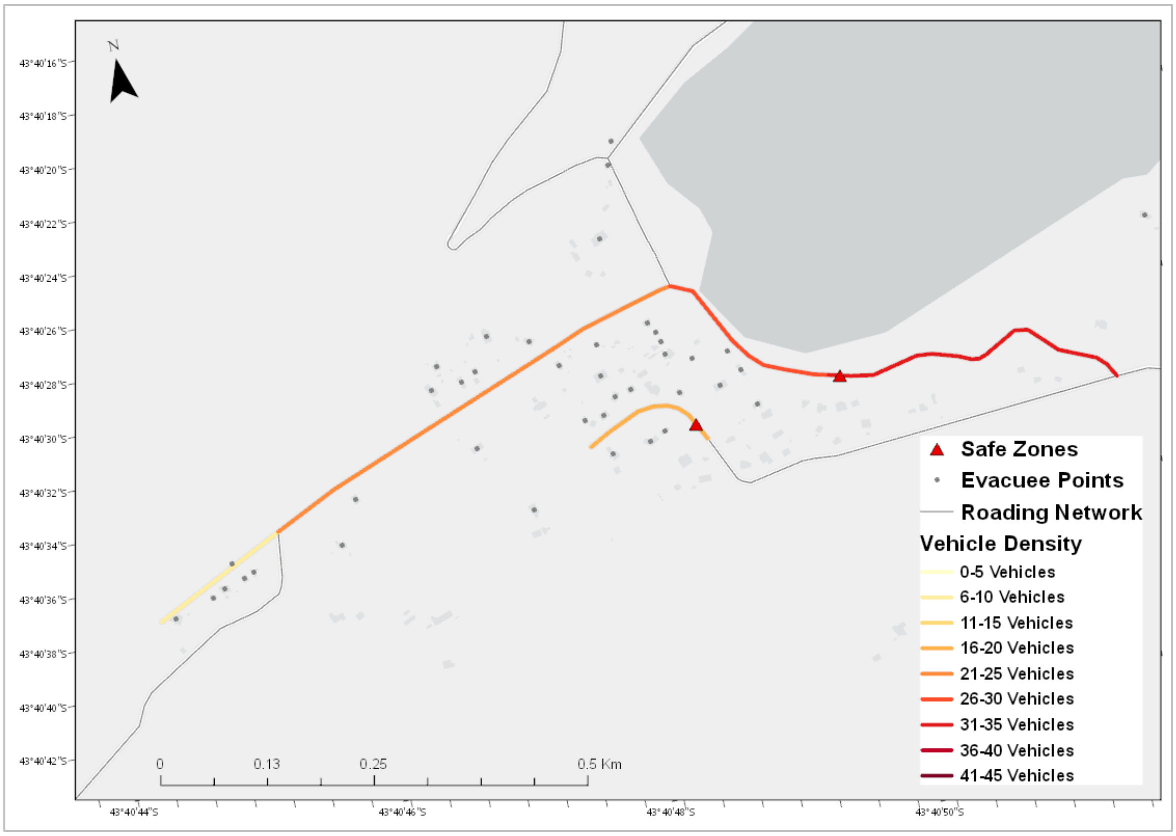

Figure 7.119: Vehicle density count results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

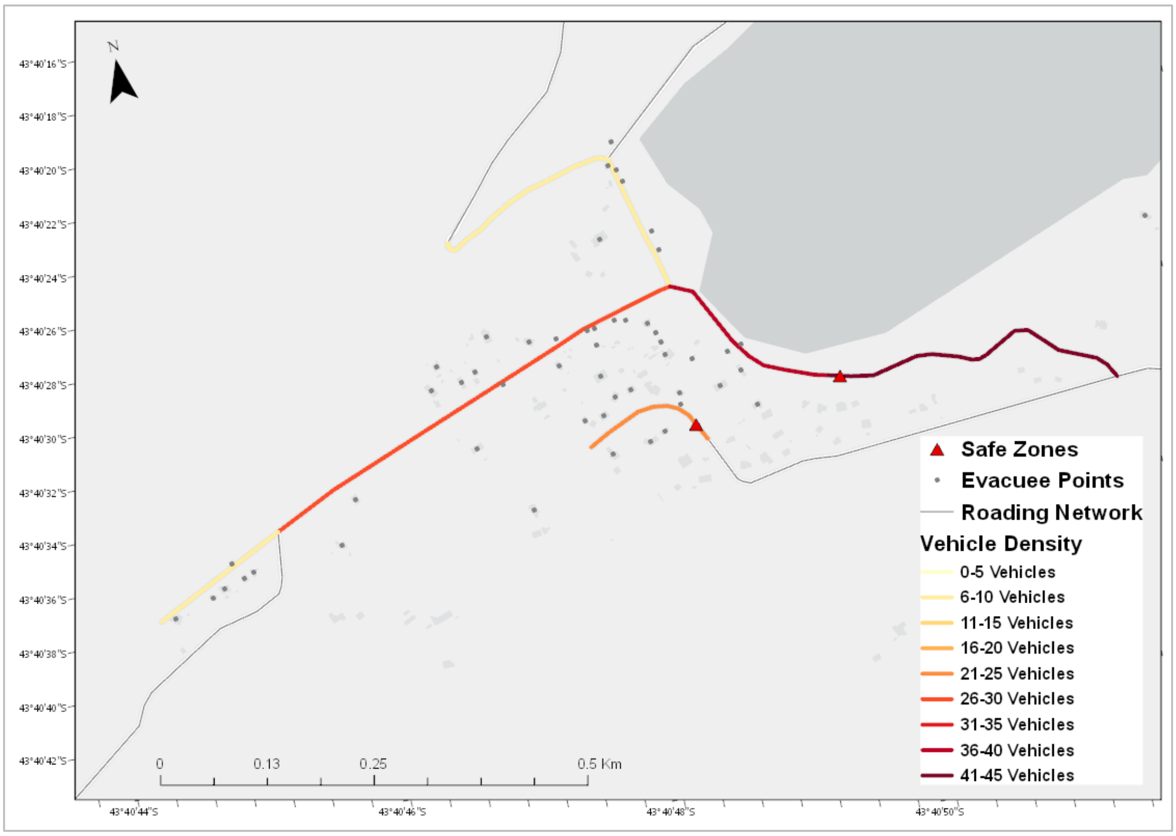

Figure 7.120: Vehicle density count results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

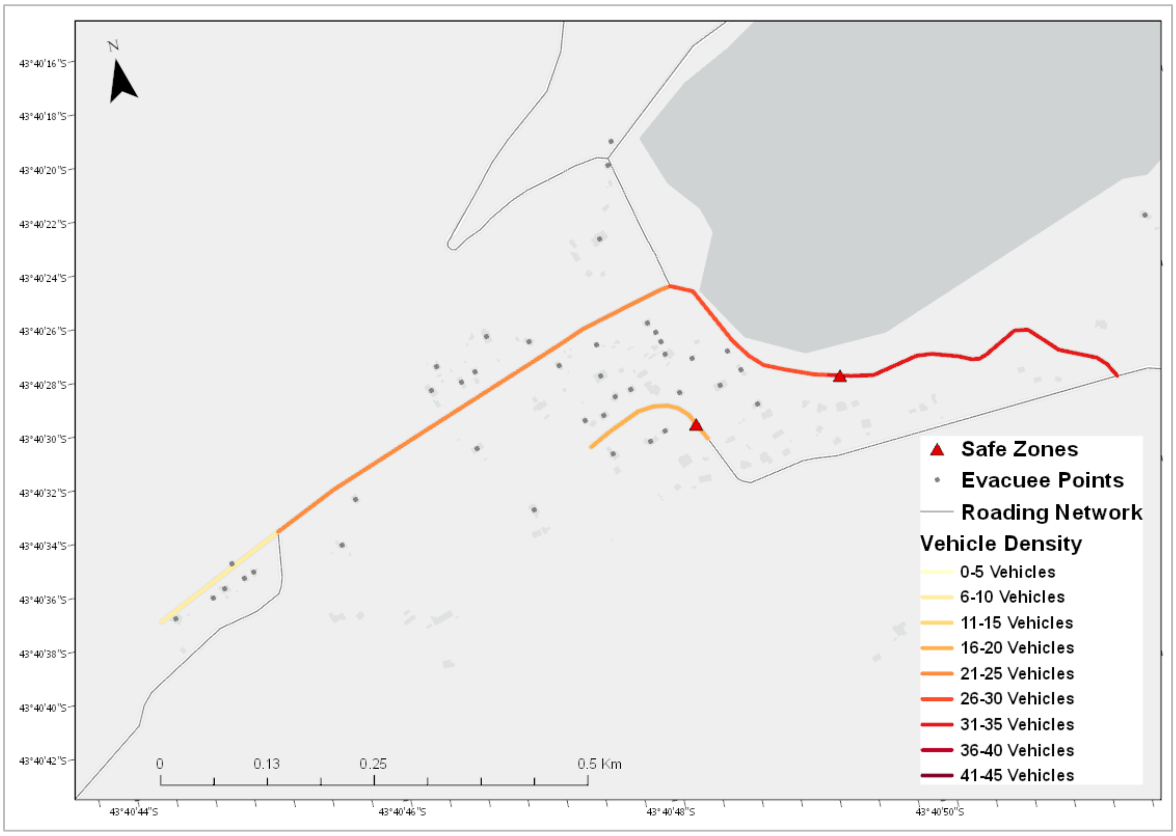

Figure 7.121: Vehicle density count results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

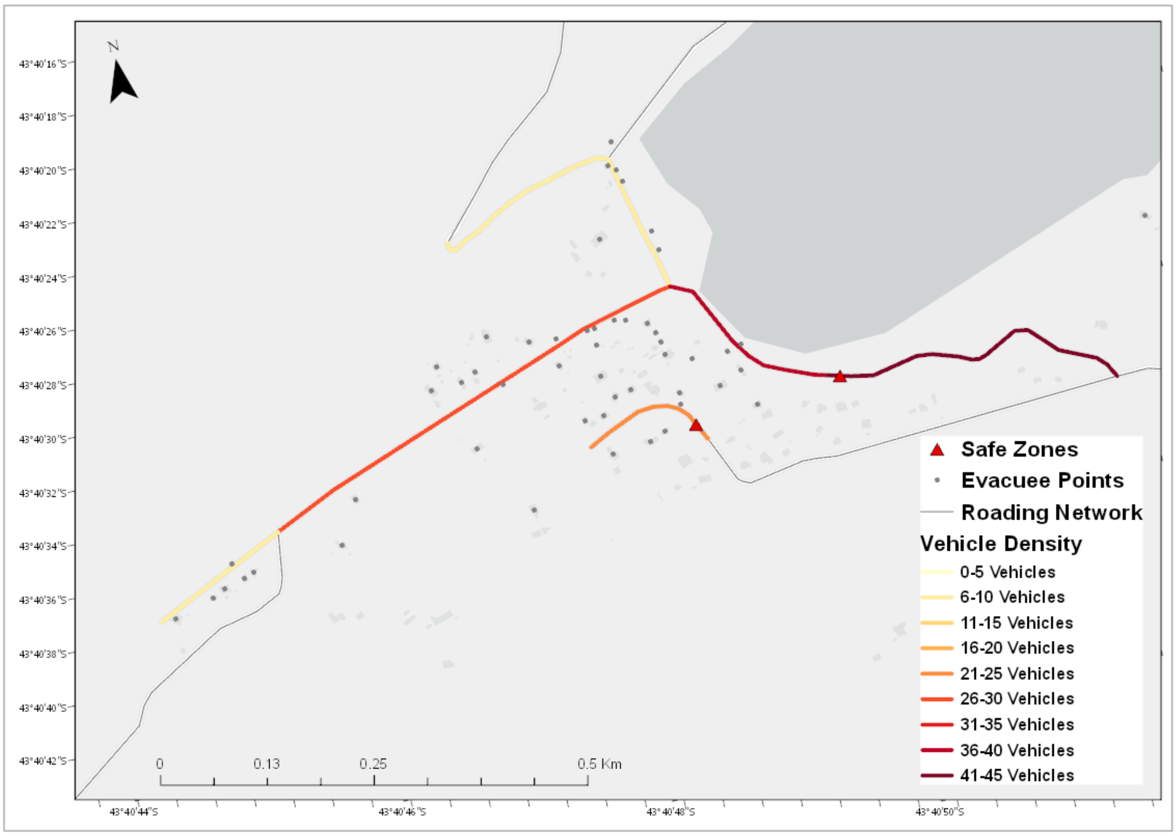

Figure 7.122: Vehicle density count results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

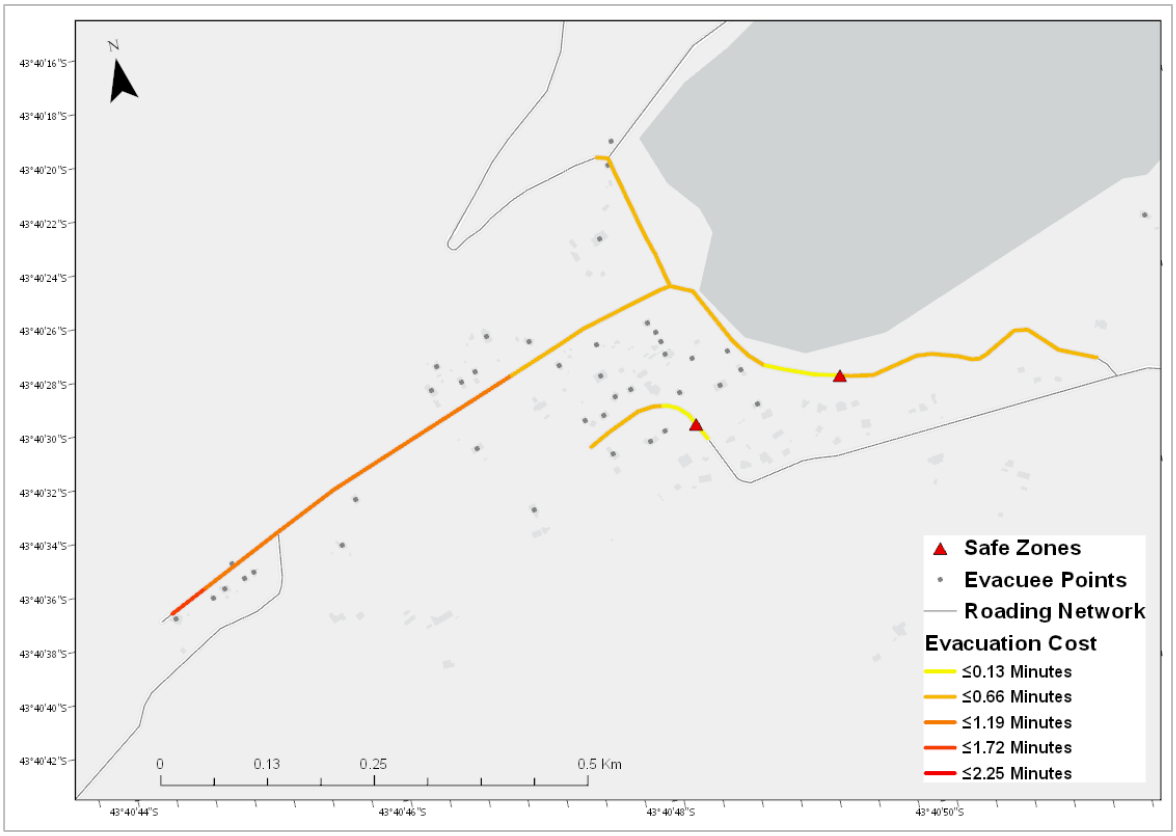

Figure 7.123: Evacuation cost results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

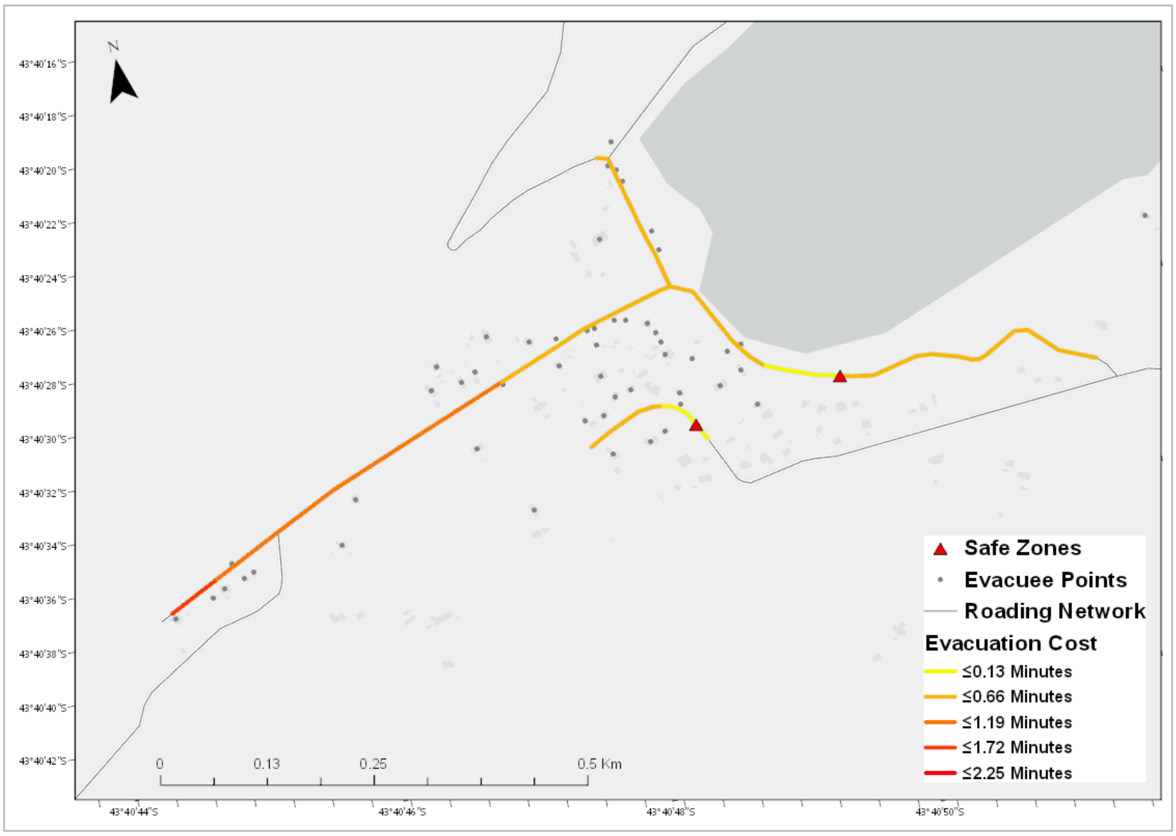

Figure 7.124: Evacuation cost results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

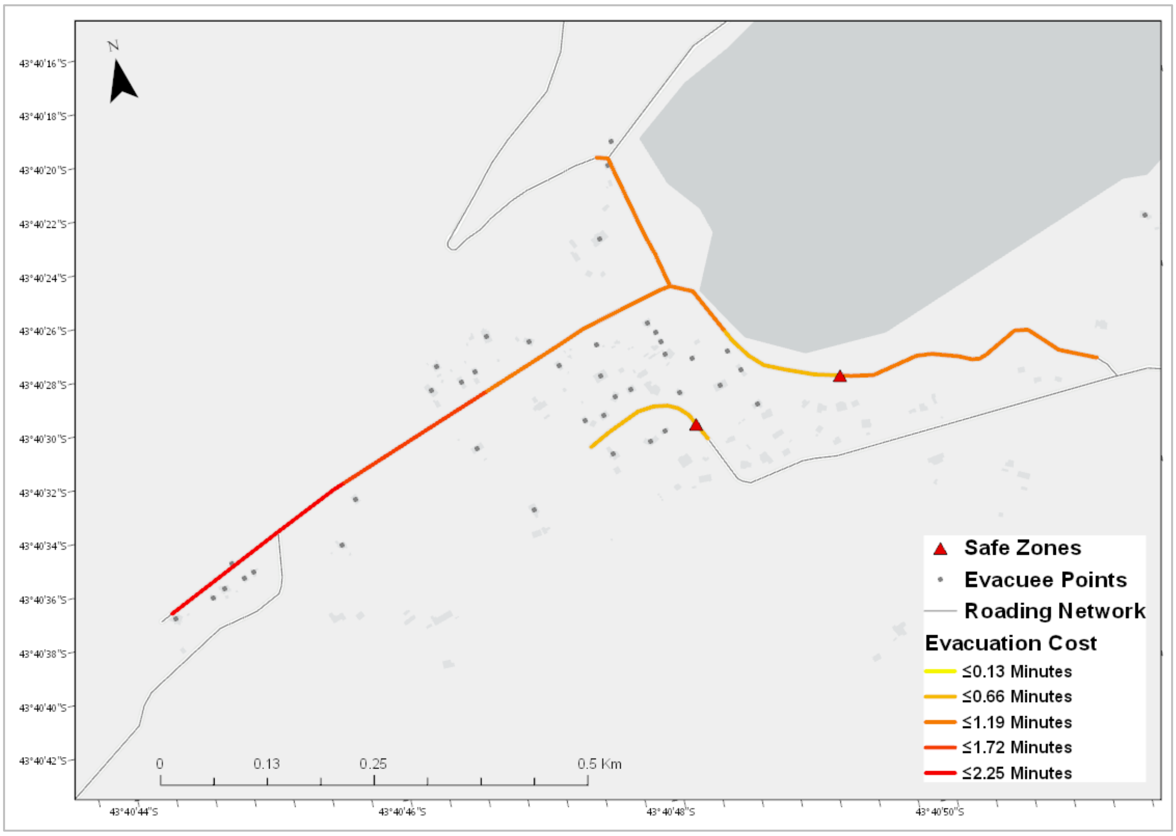

Figure 7.125: Evacuation cost results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

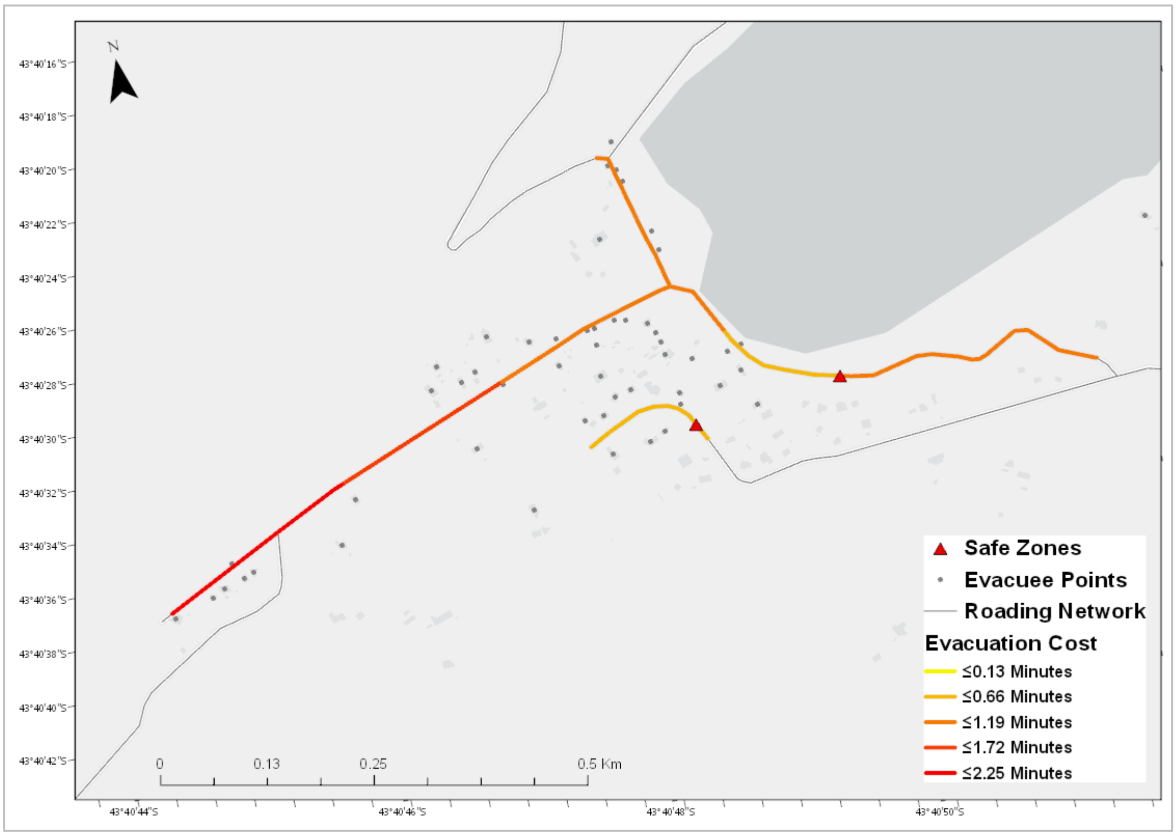

Figure 7.126: Evacuation cost results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

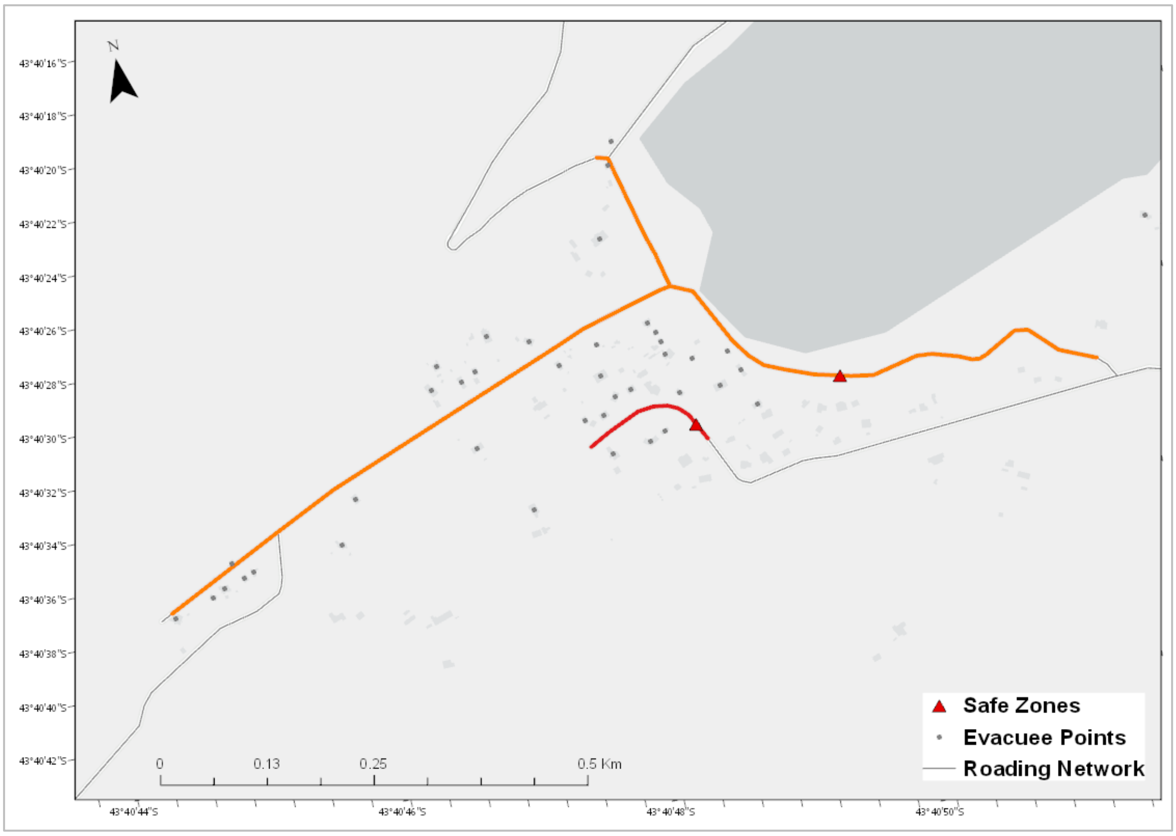

Figure 7.127: Safe zone distribution results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

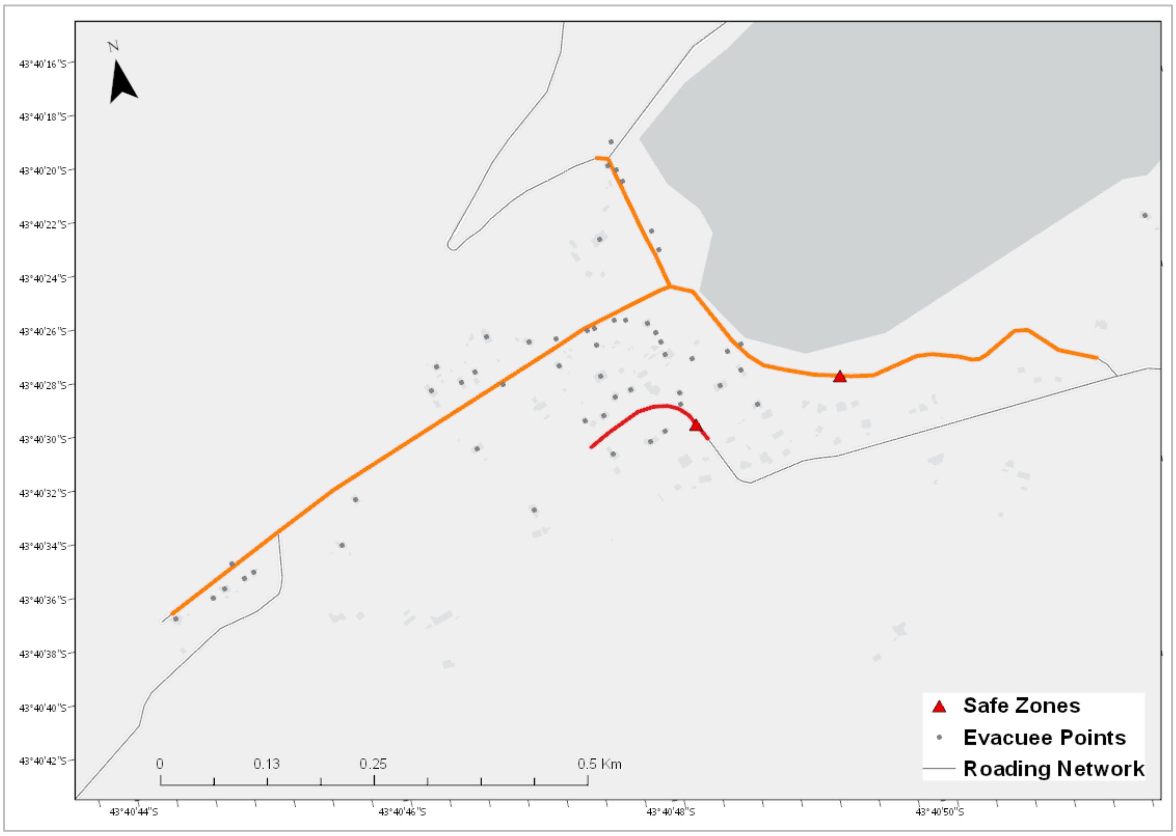

Figure 7.128: Safe zone distribution results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

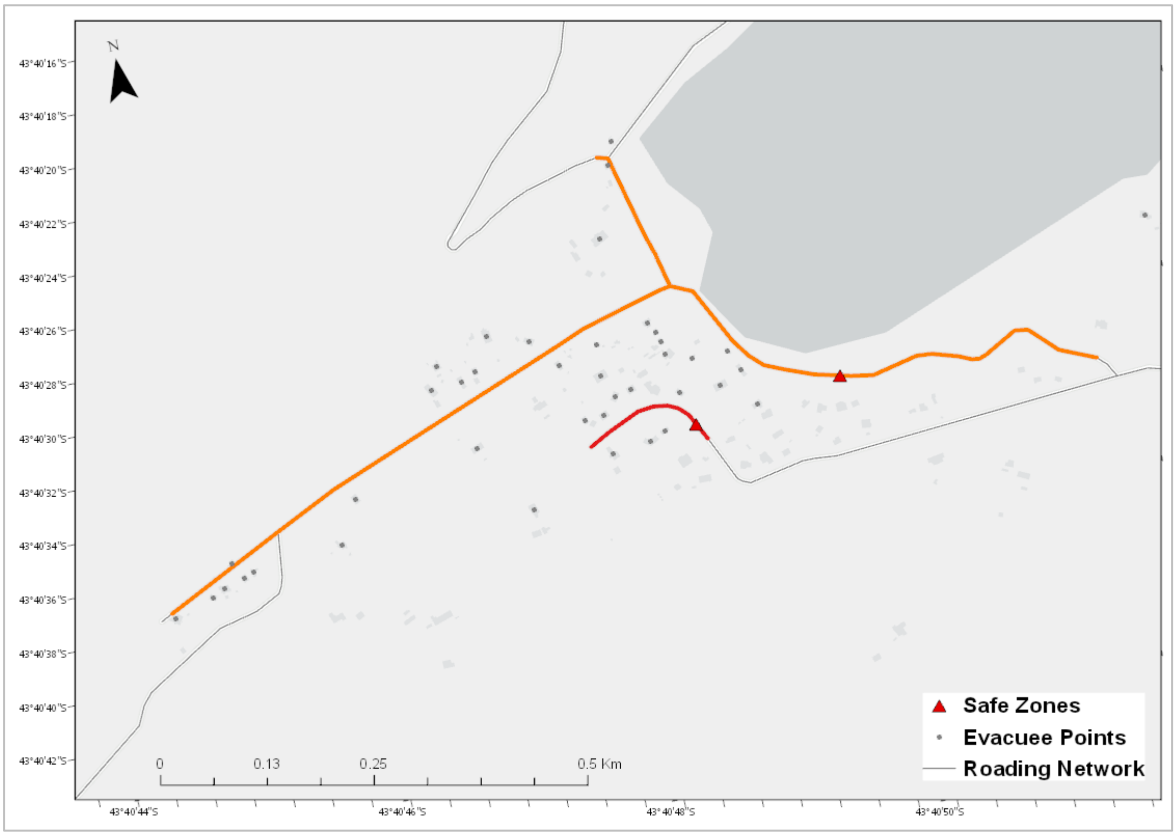

Figure 7.129: Safe zone distribution results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

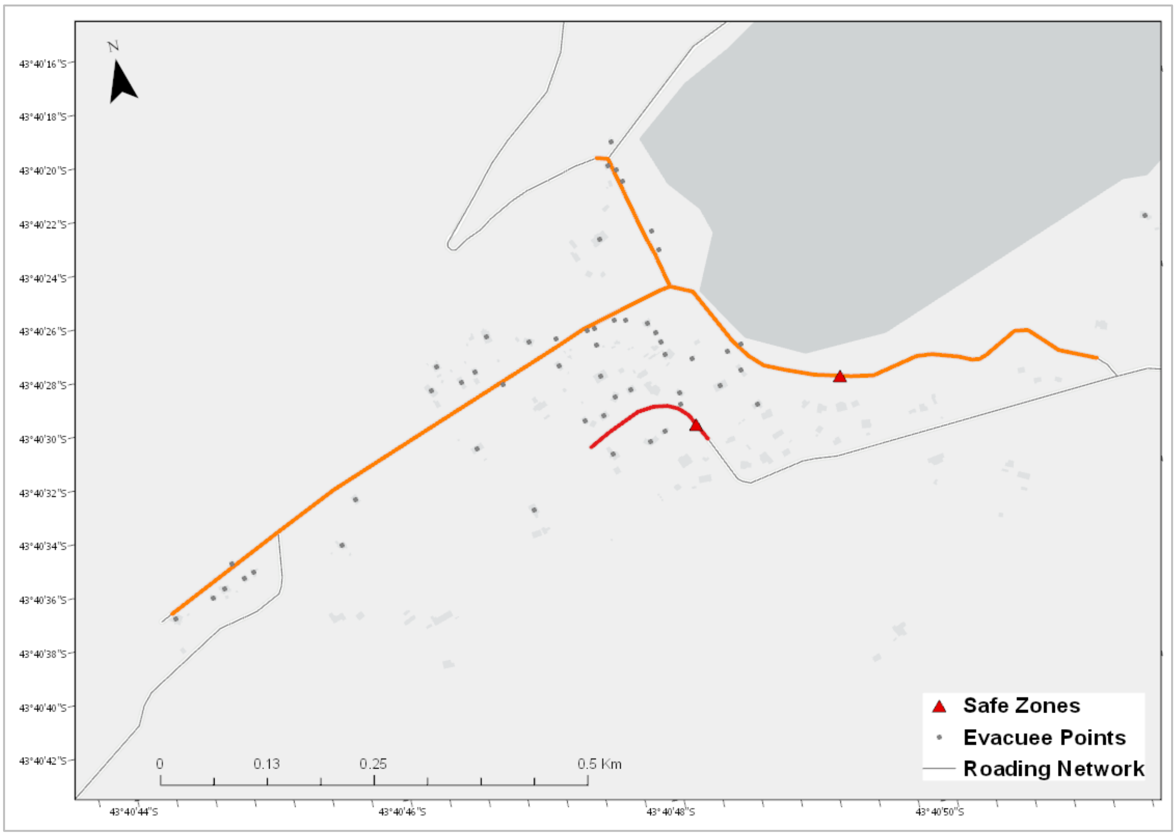

Figure 7.130: Safe zone distribution results for Little Akaloa when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

f. Okains Bay

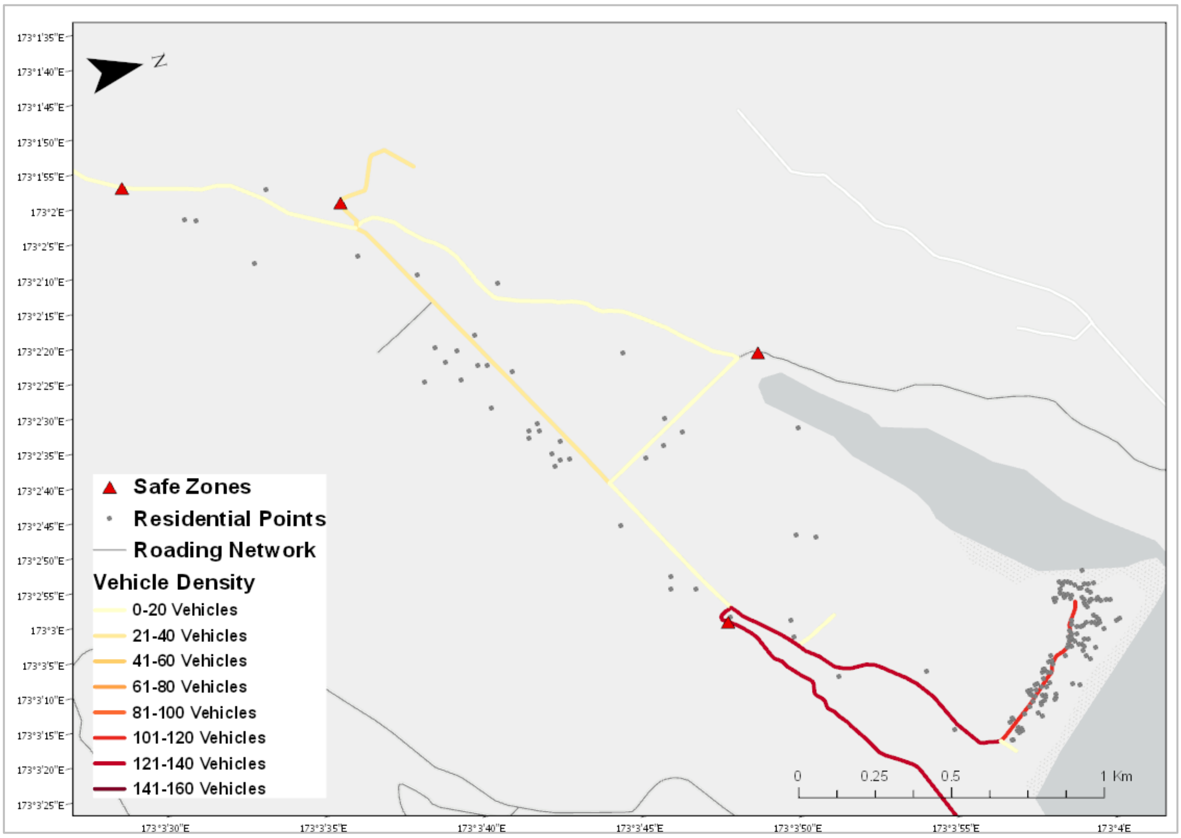

Figure 7.131: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

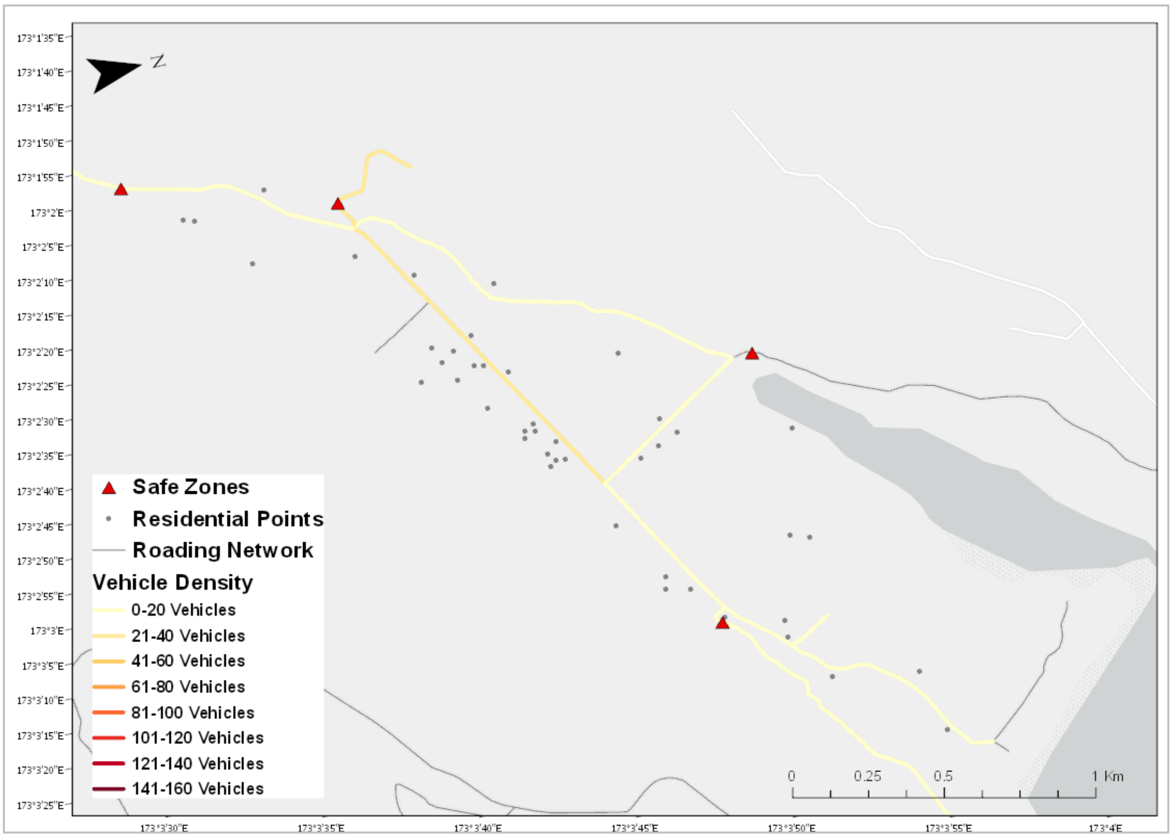

Figure 7.132: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

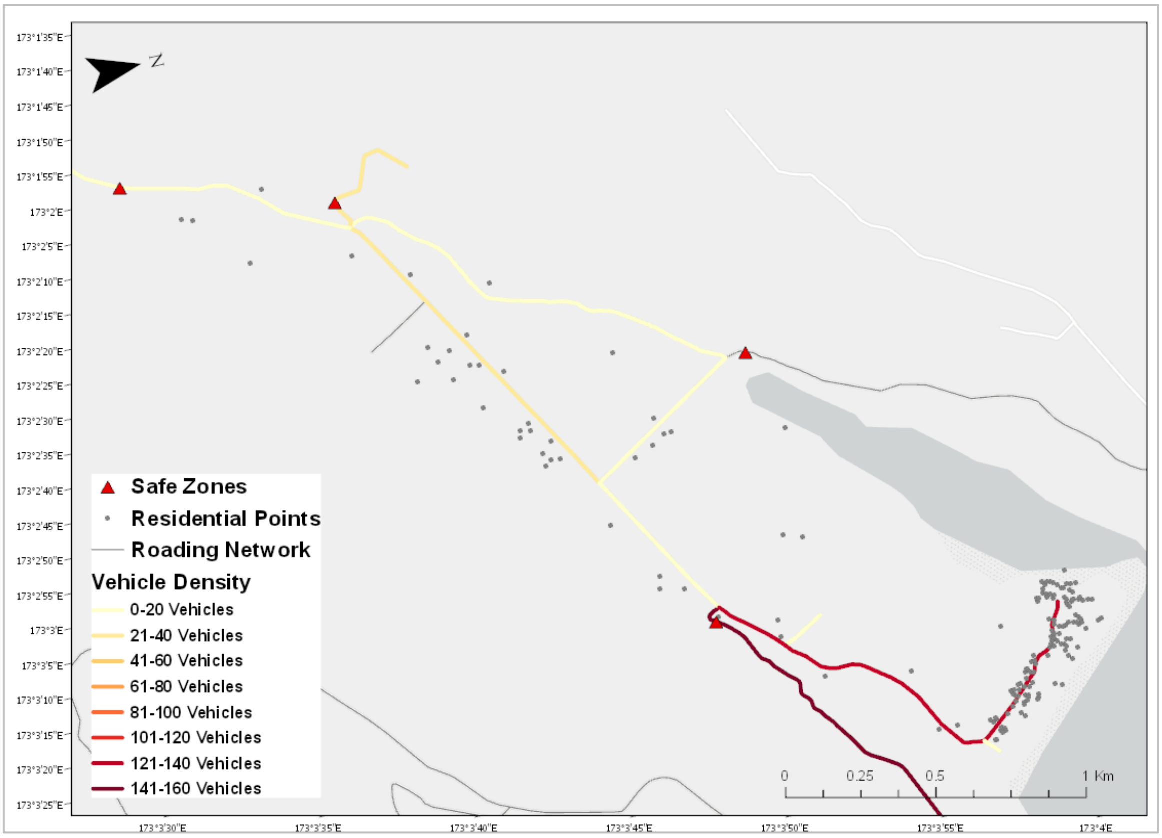

Figure 7.133: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

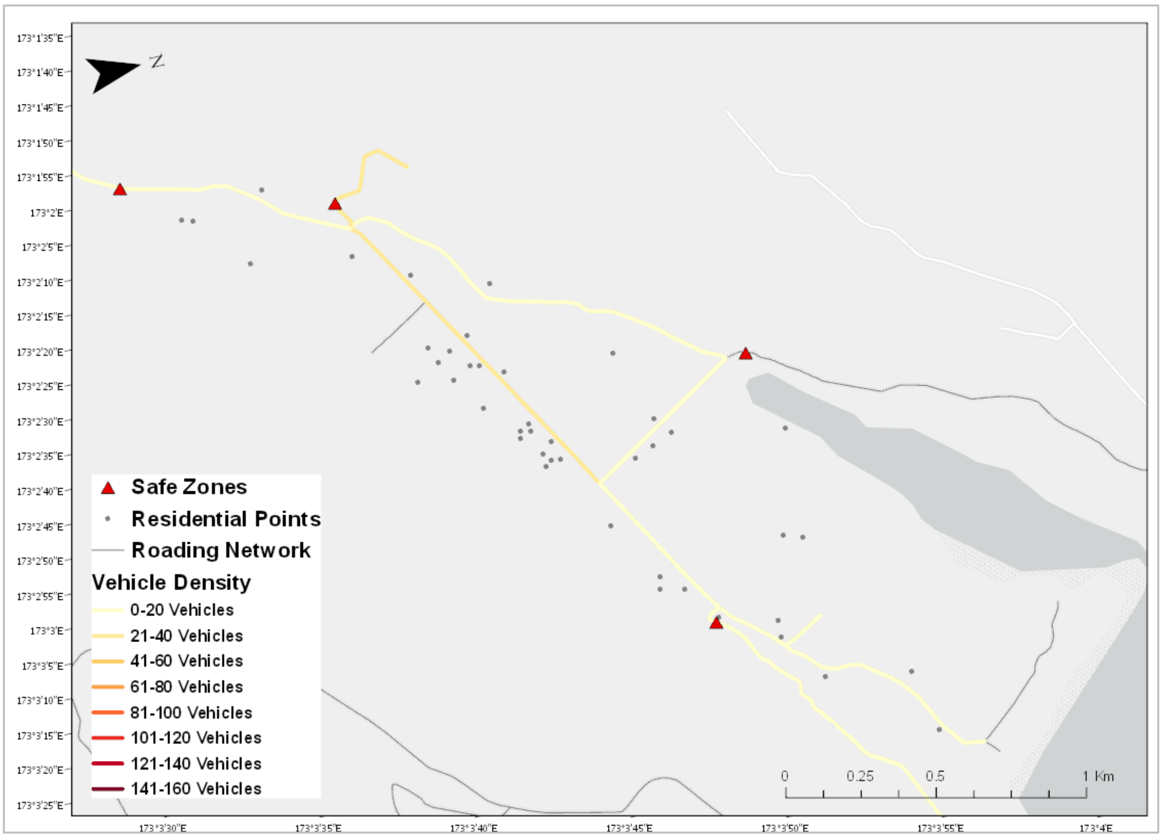

Figure 7.134: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

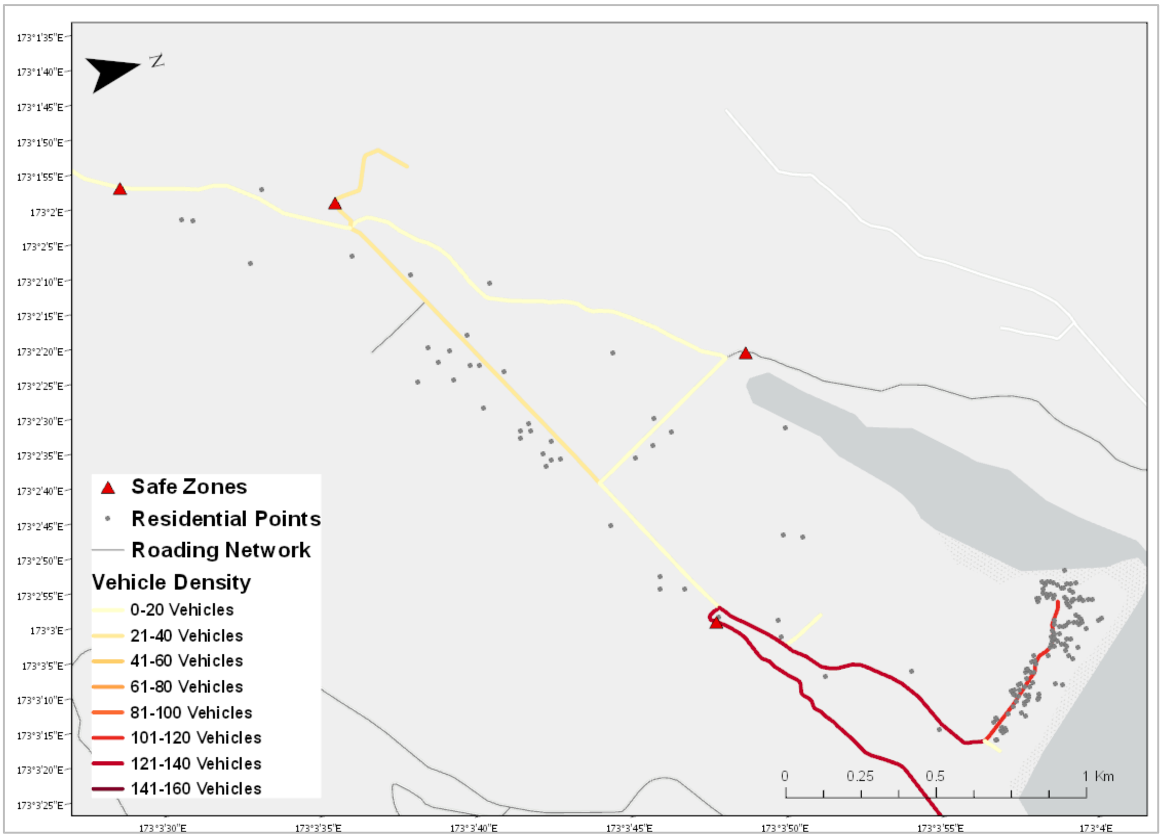

Figure 7.135: Vehicle density count results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

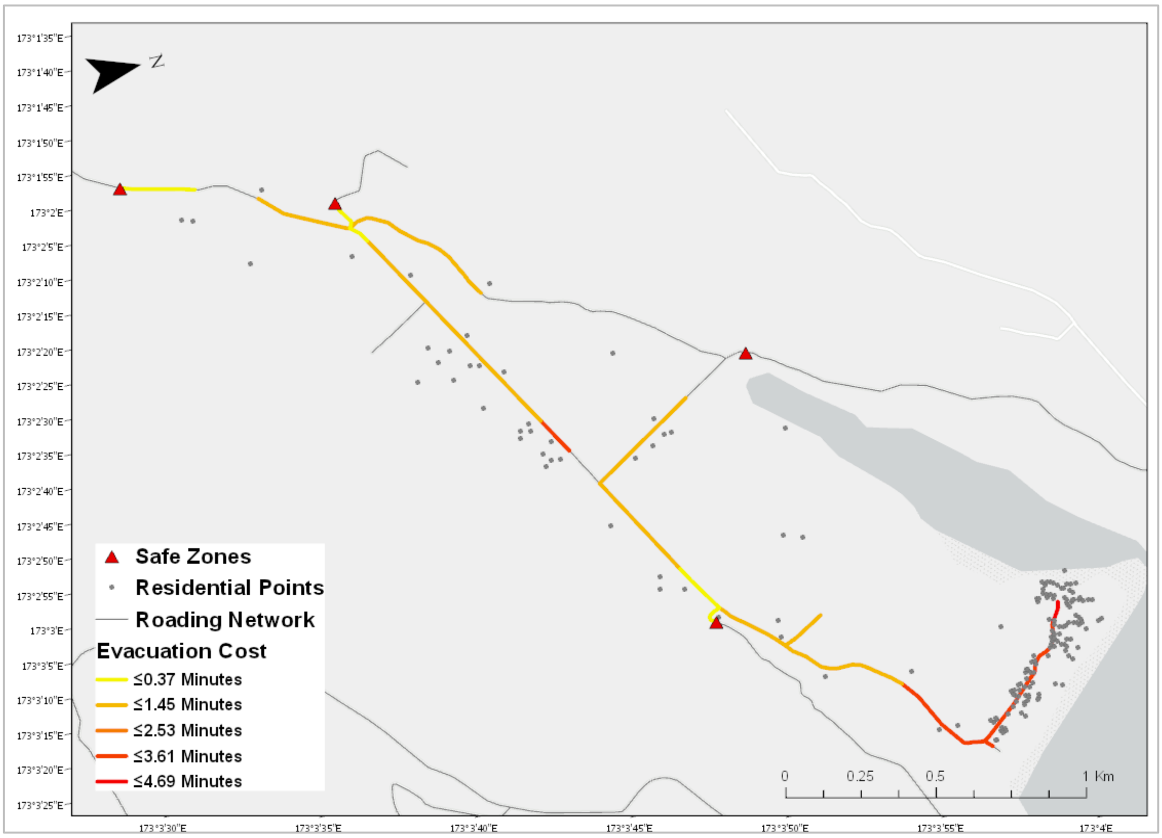

Figure 7.136: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

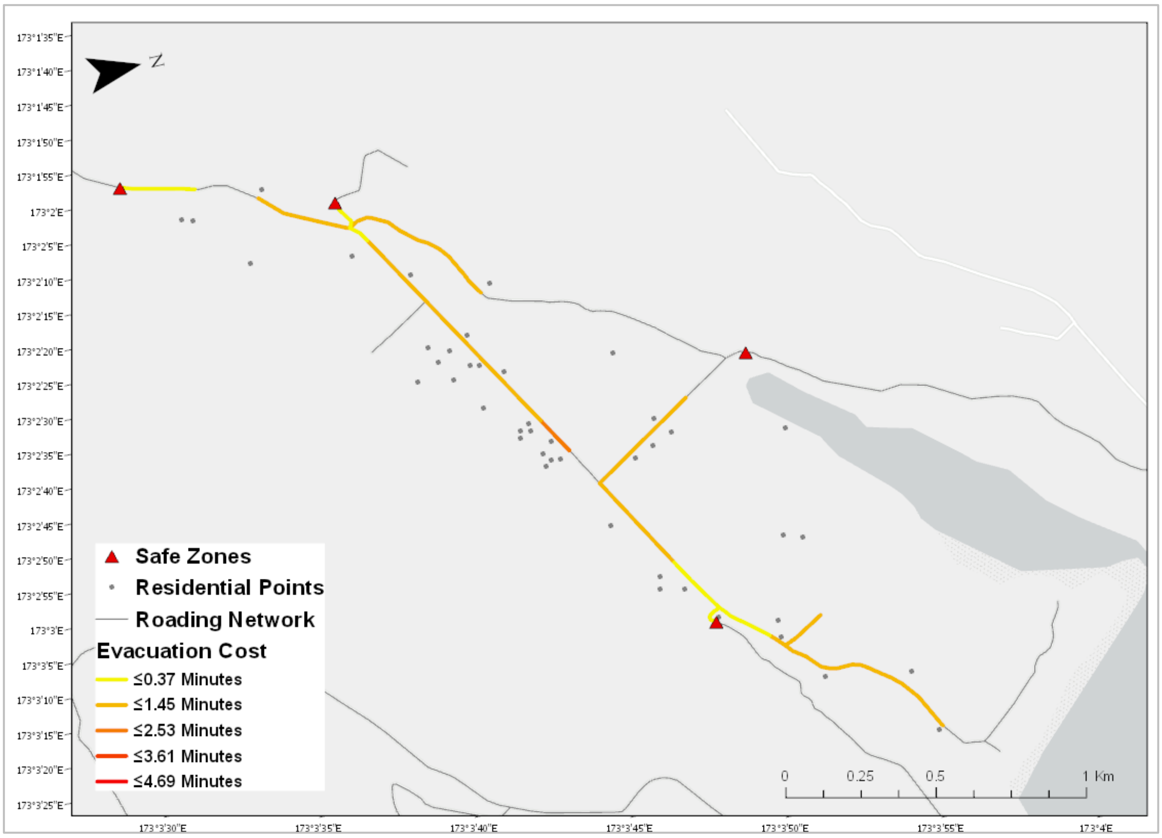

Figure 7.137: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

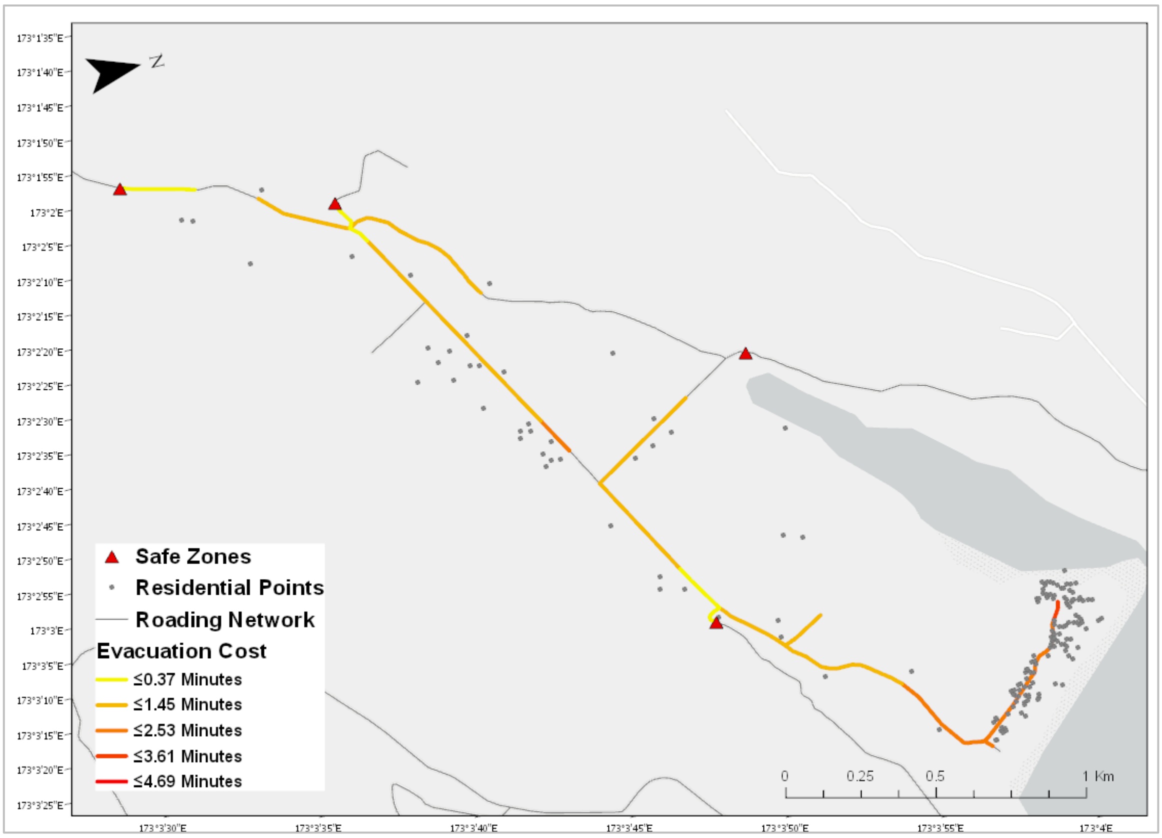

Figure 7.138: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

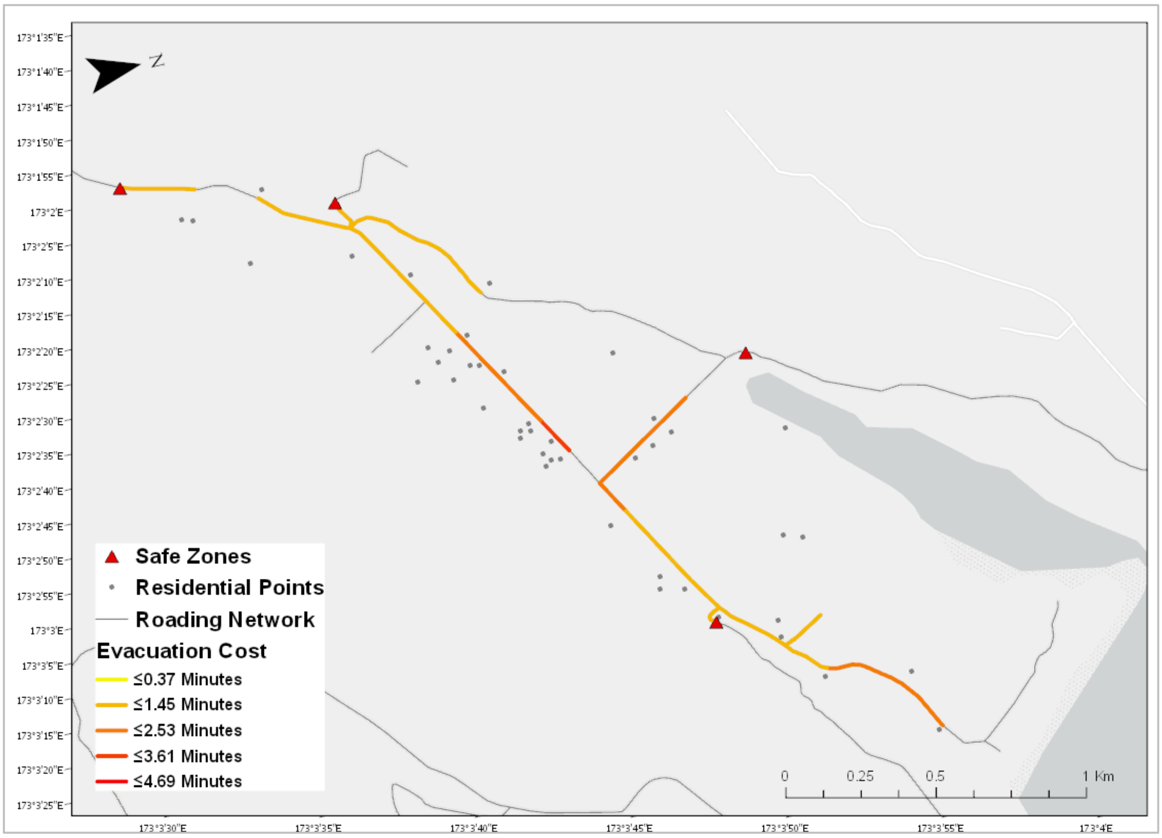

Figure 7.139: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

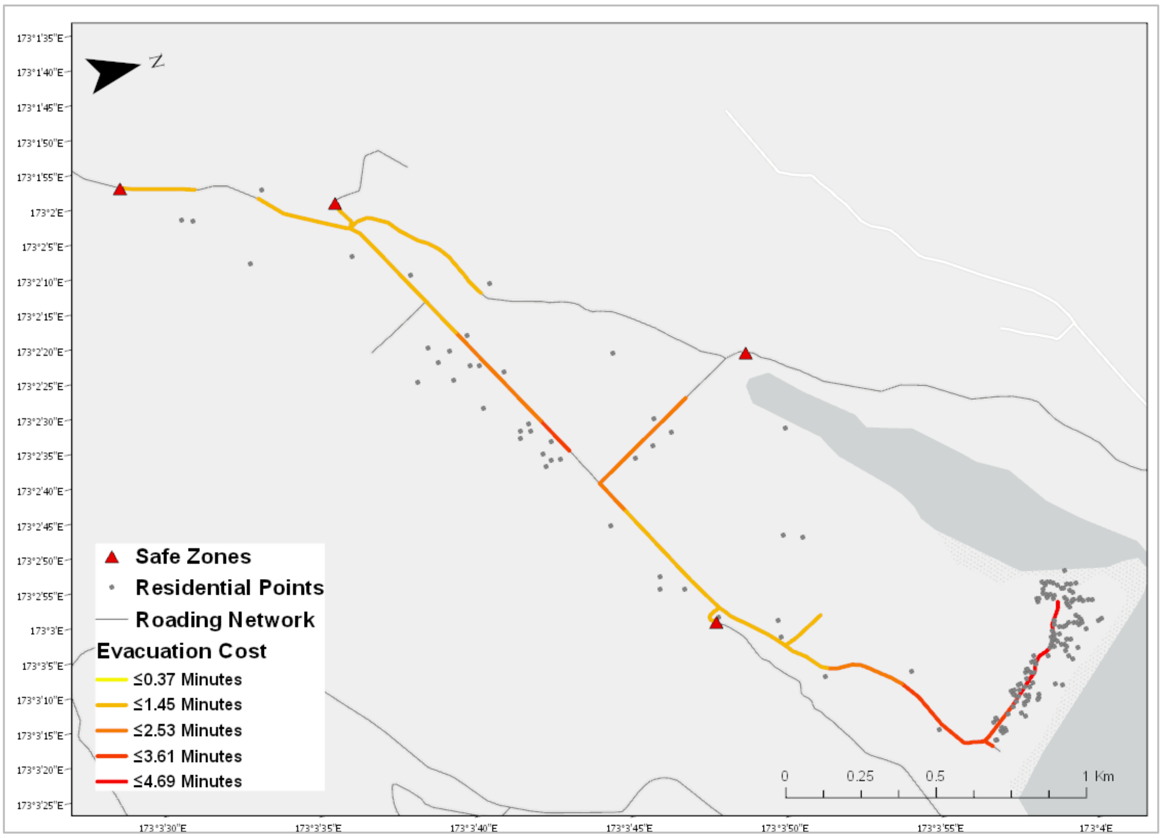

Figure 7.140: Evacuation cost results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

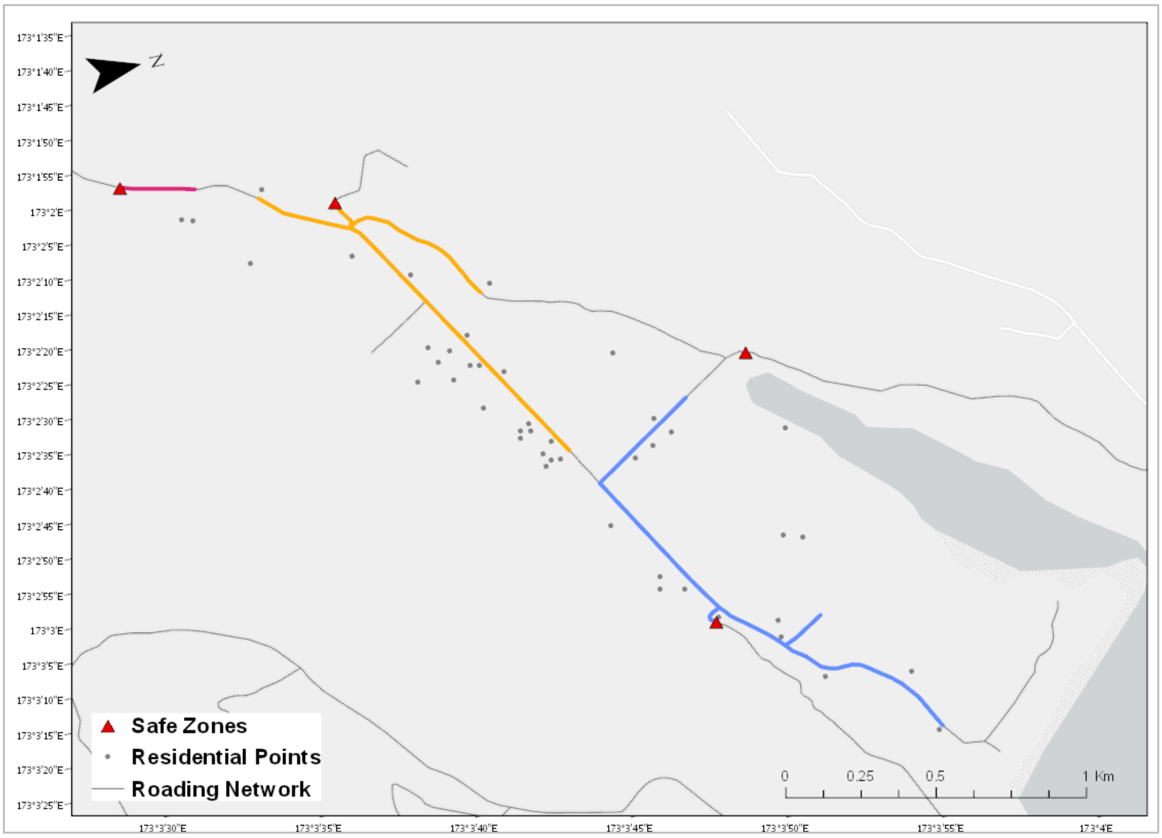

Figure 7.141: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

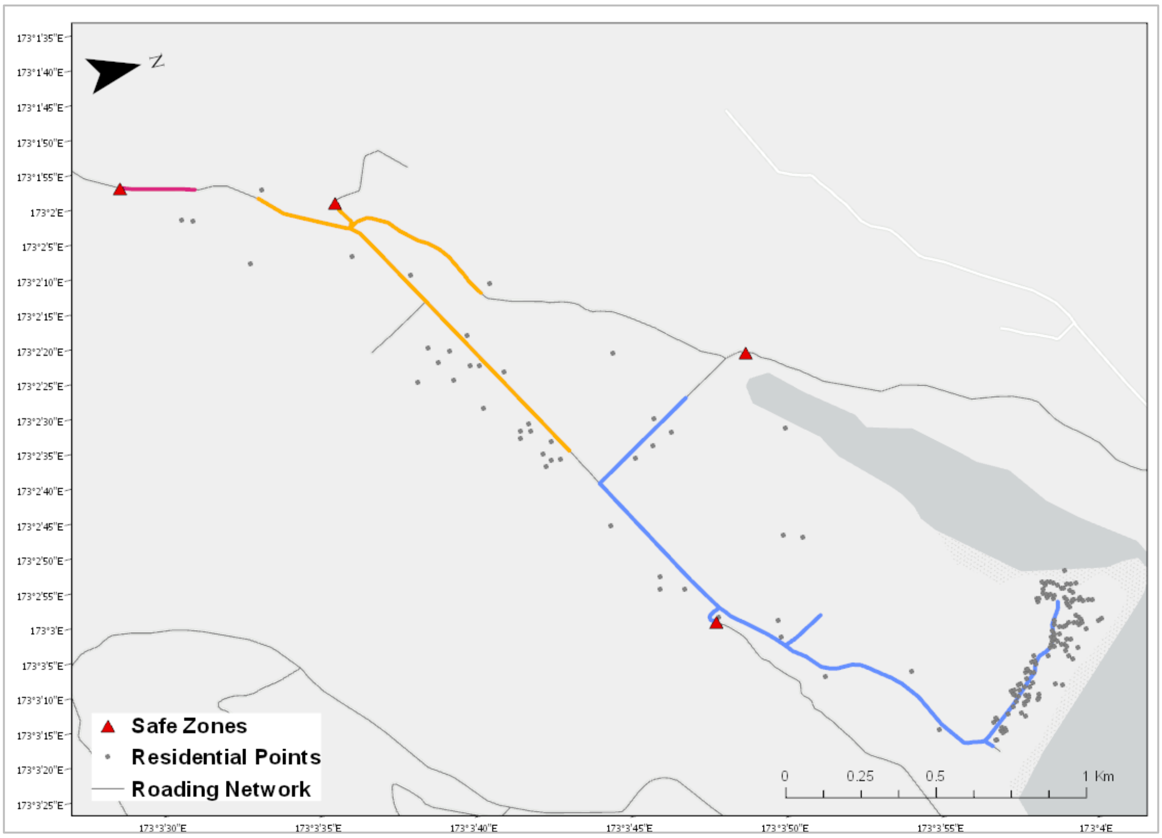

Figure 7.142: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

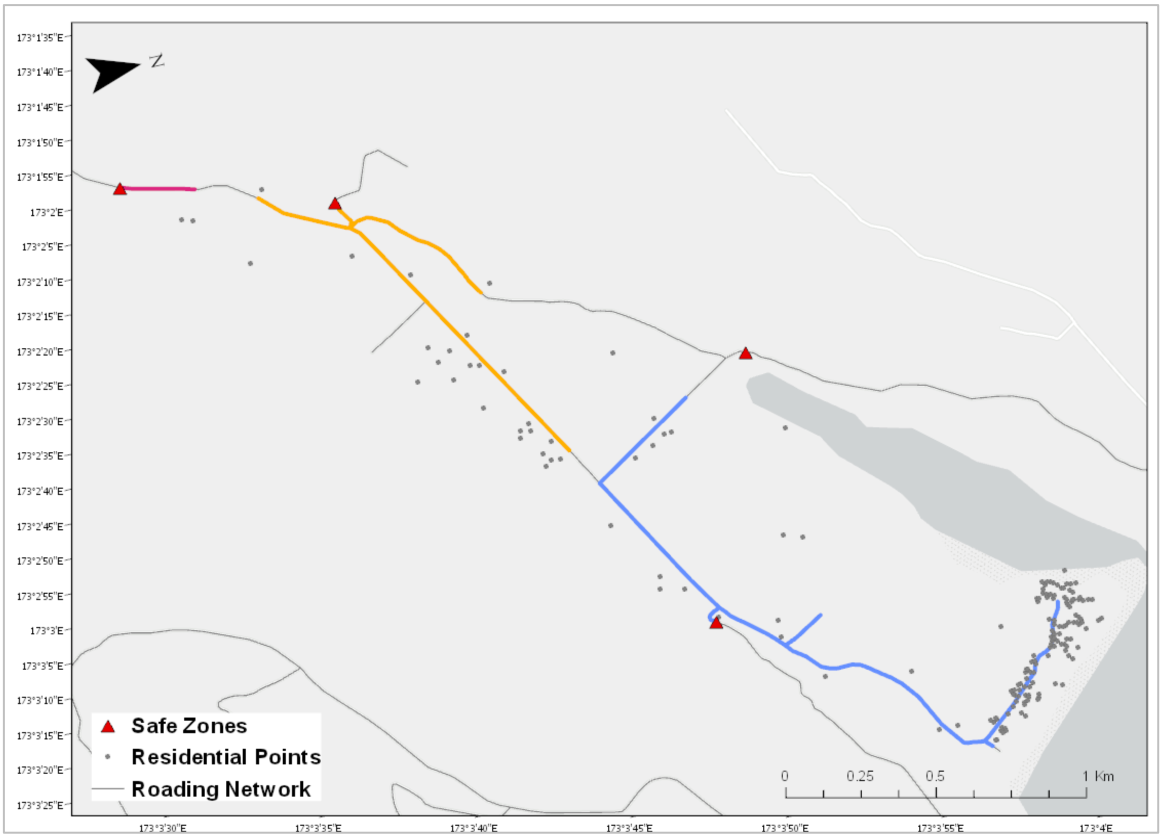

Figure 7.143: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

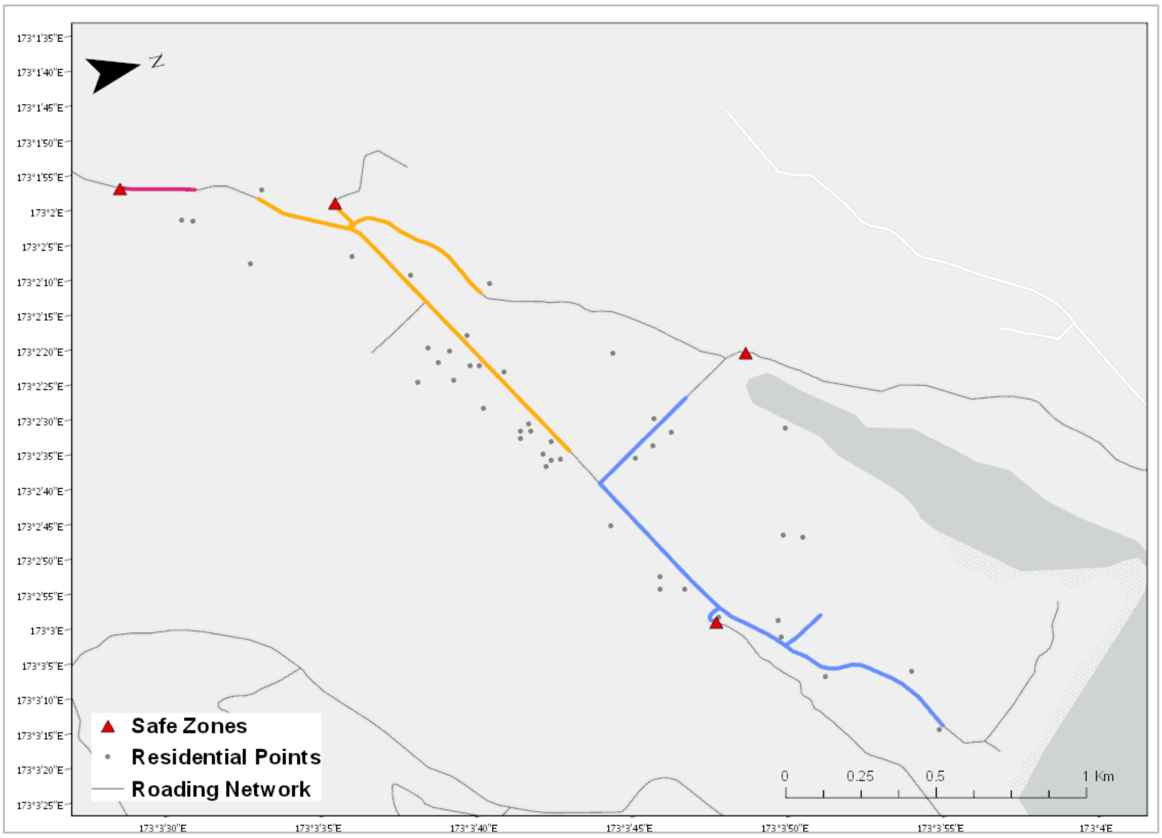

Figure 7.144: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

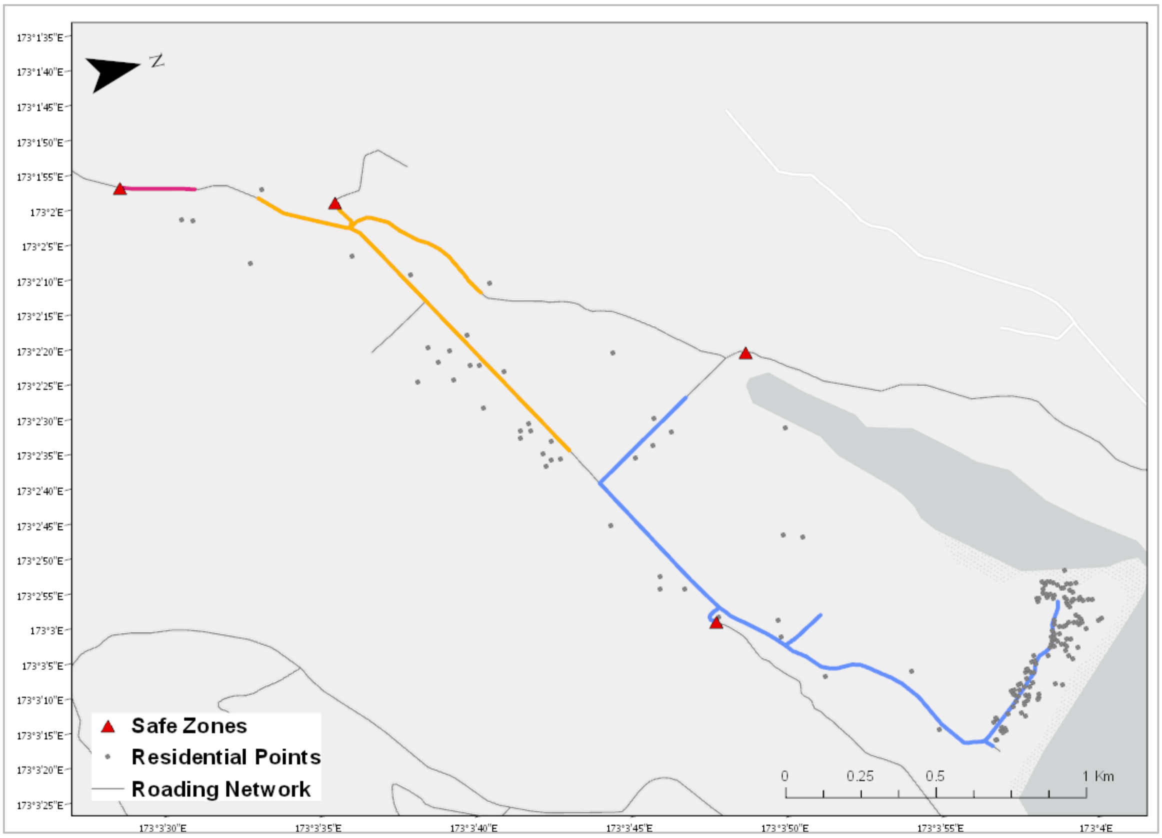

Figure 7.145: Safe zone distribution results for Okains Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

v. Reduced Safe Zones

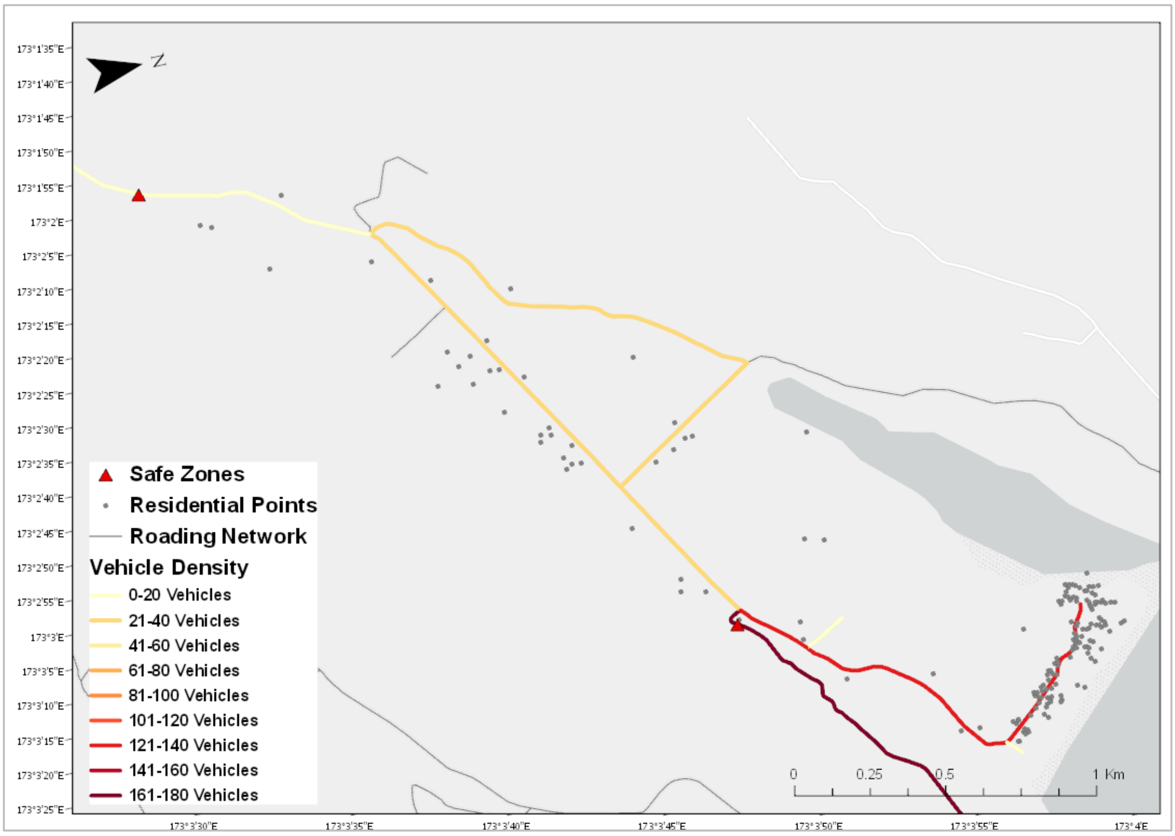

Figure 7.146: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

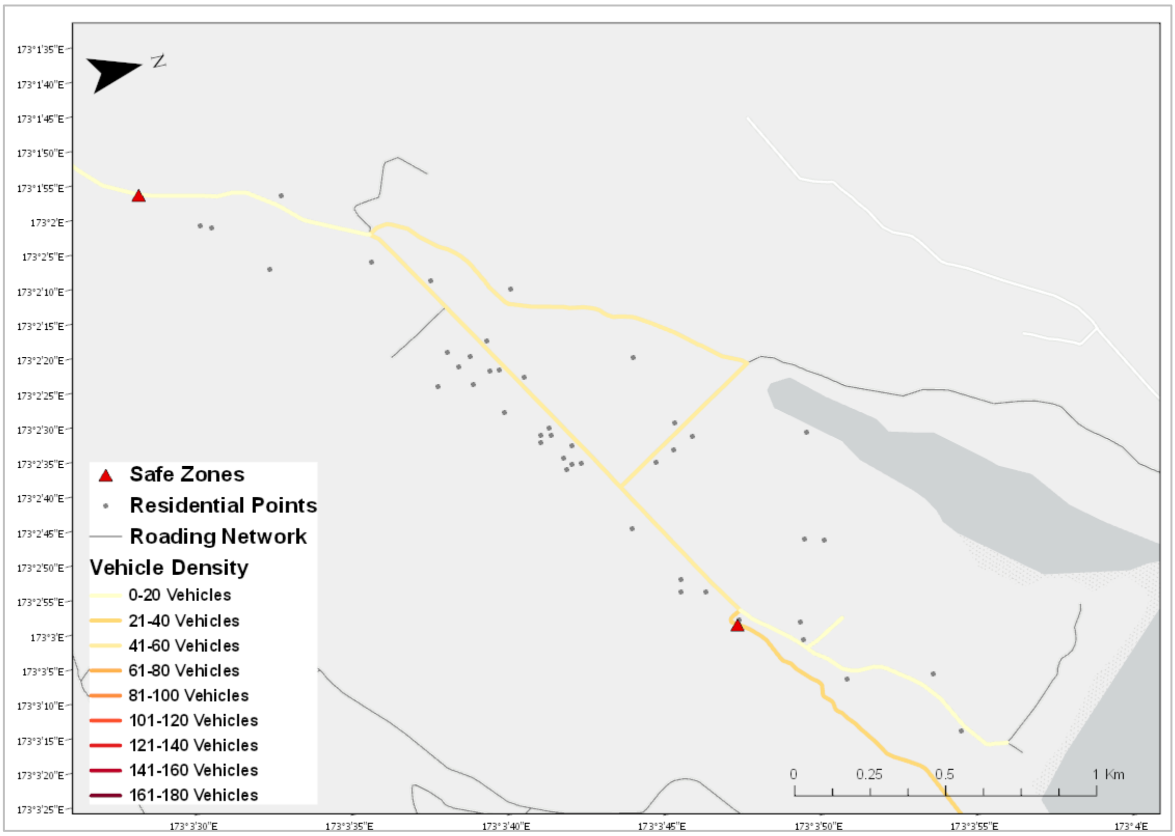

Figure 7.147: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

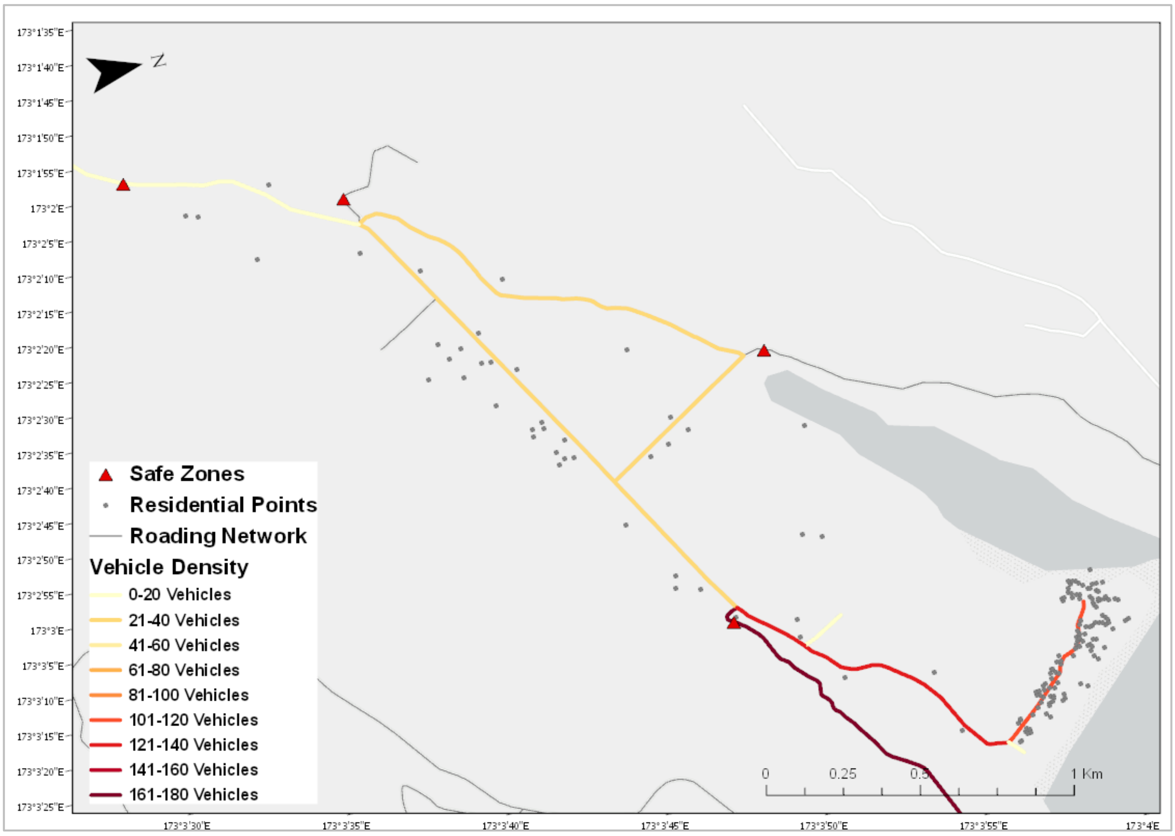

Figure 7.148: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

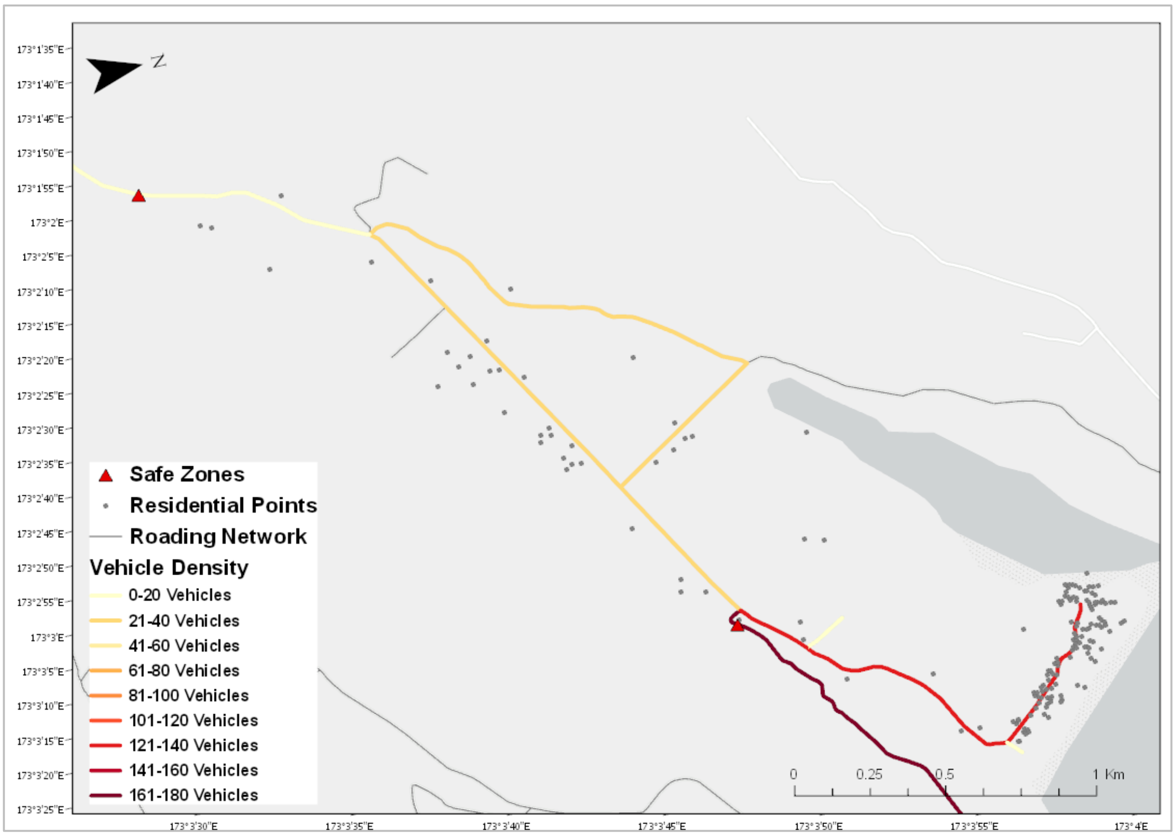

Figure 7.149: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

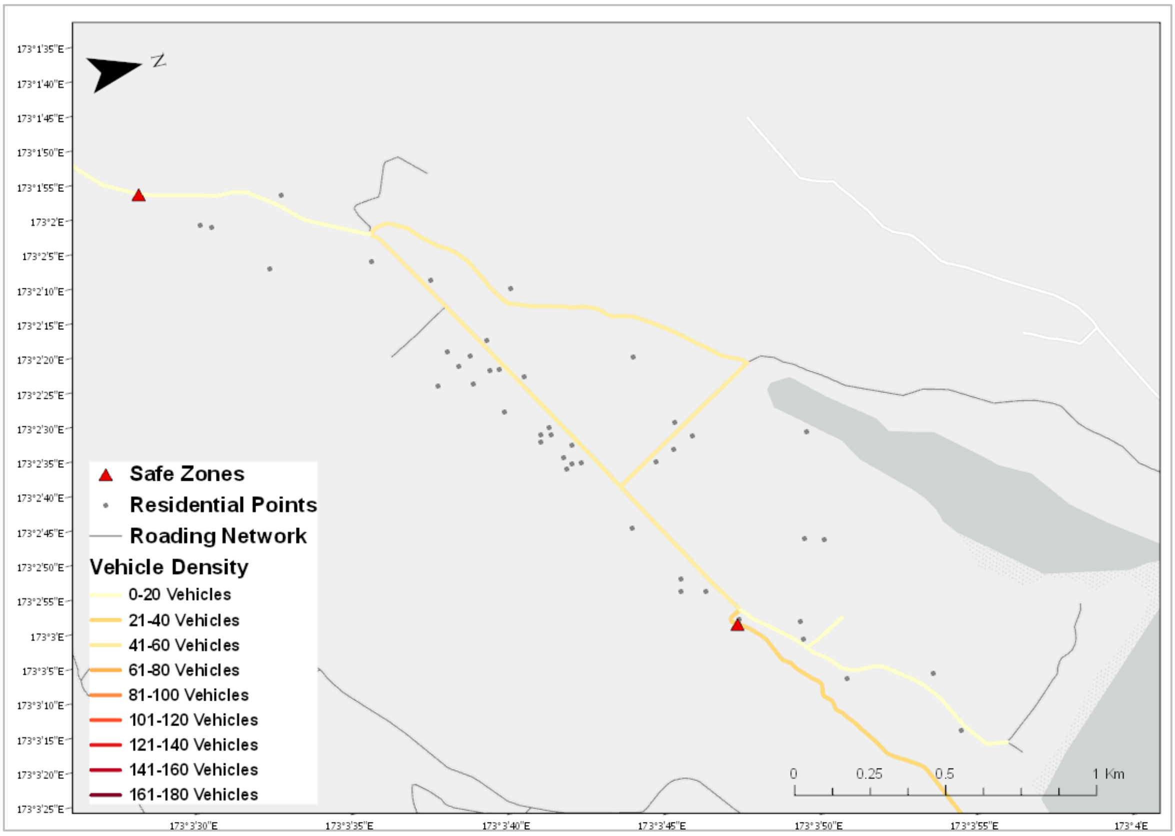

Figure 7.150: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

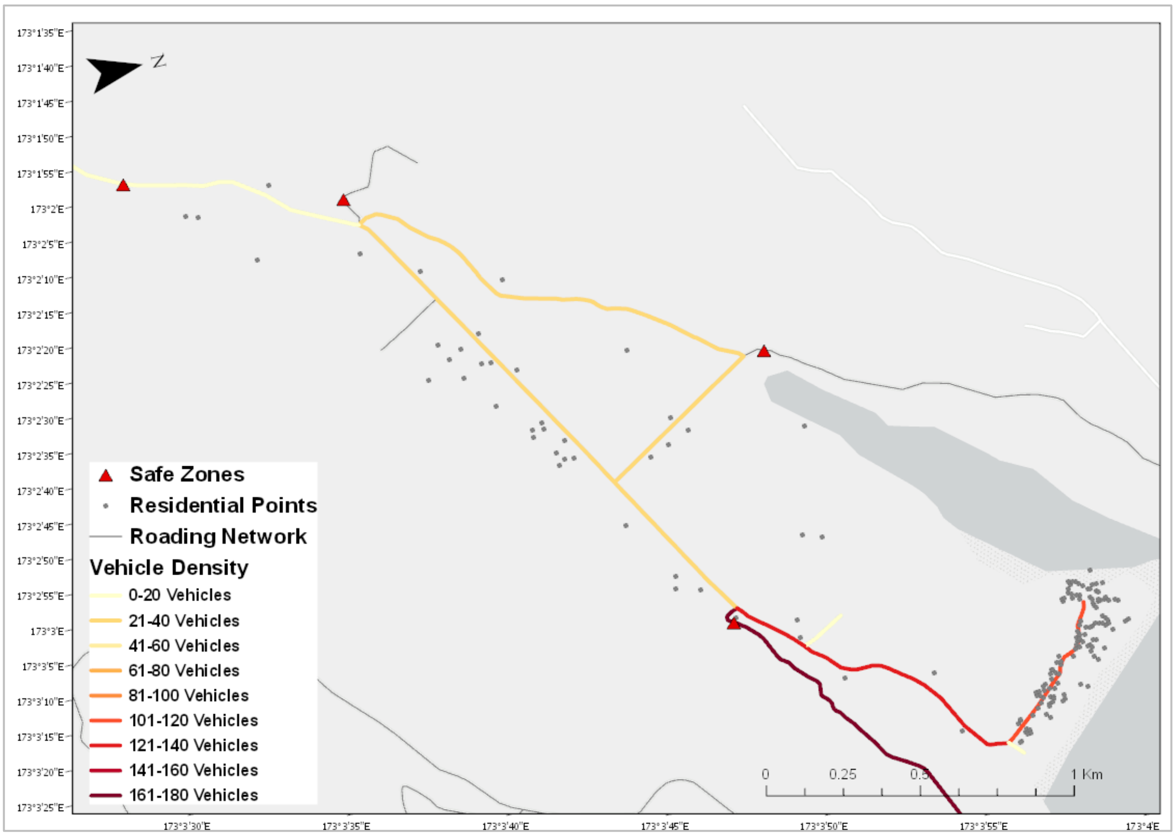

Figure 7.151: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

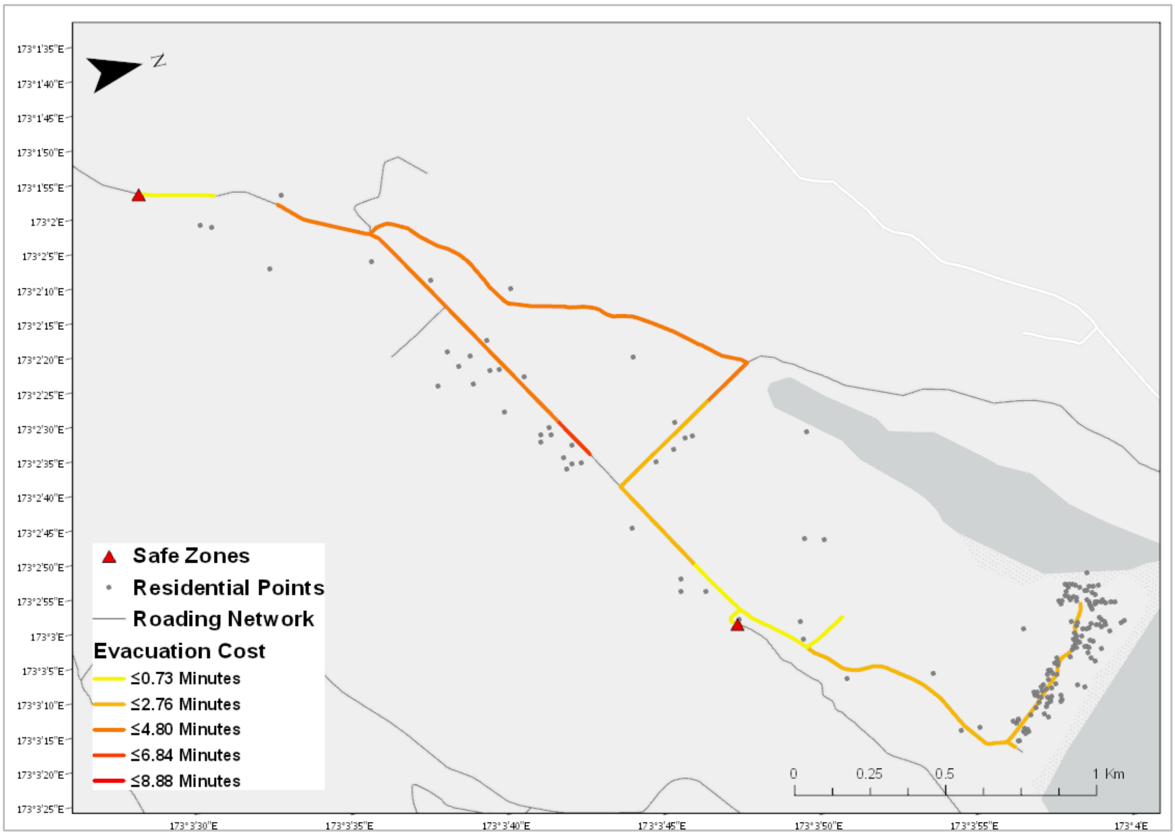

Figure 7.152: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

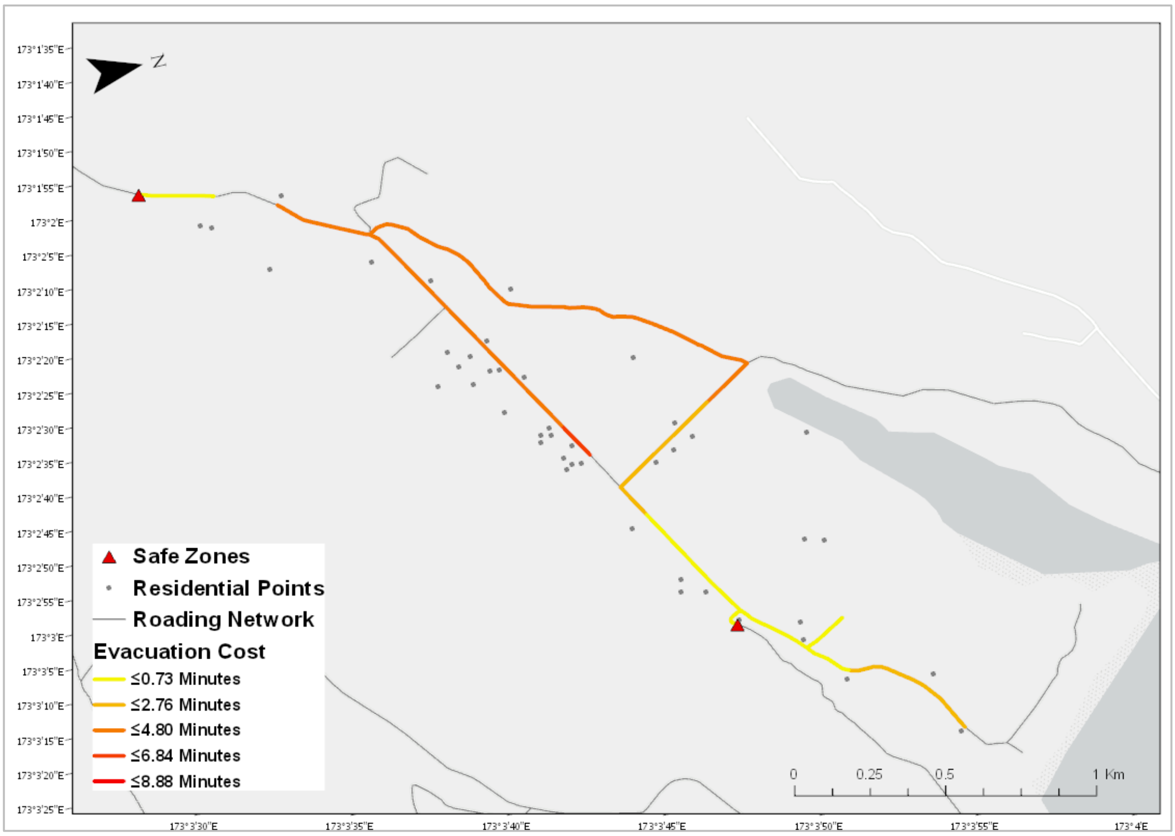

Figure 7.153: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

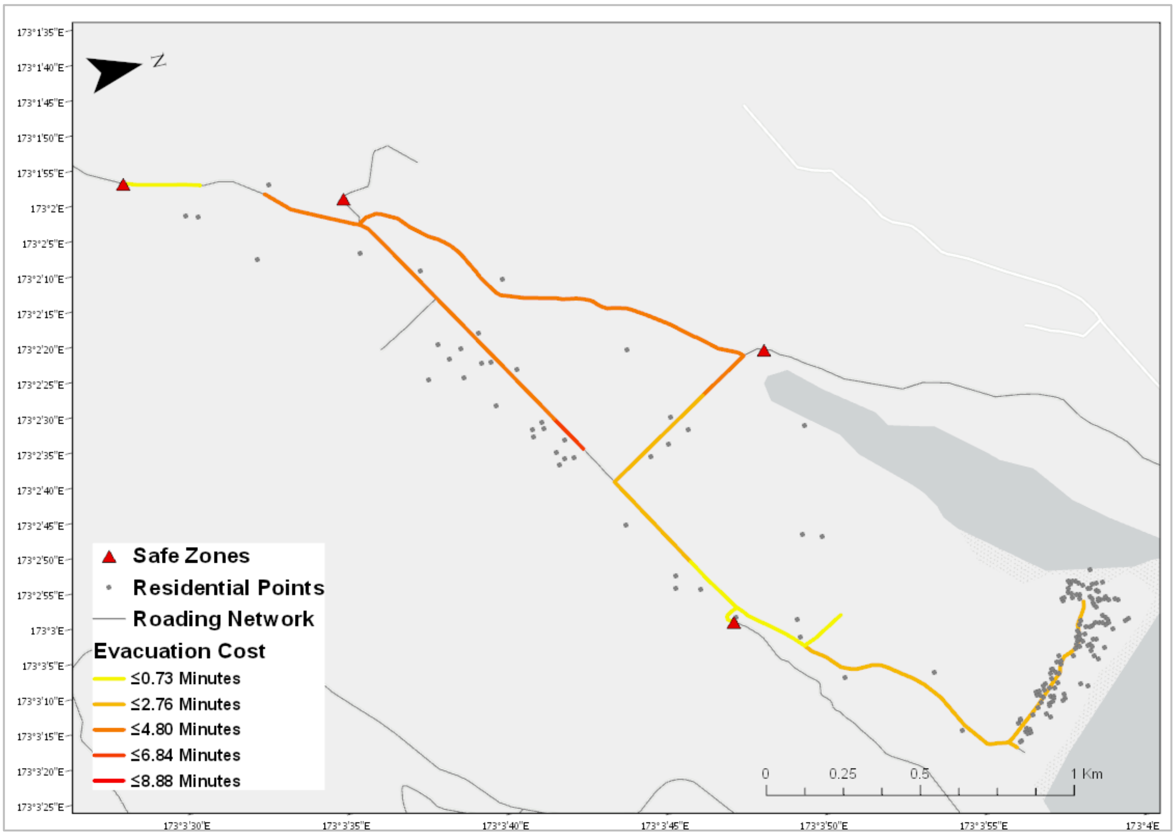

Figure 7.154: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

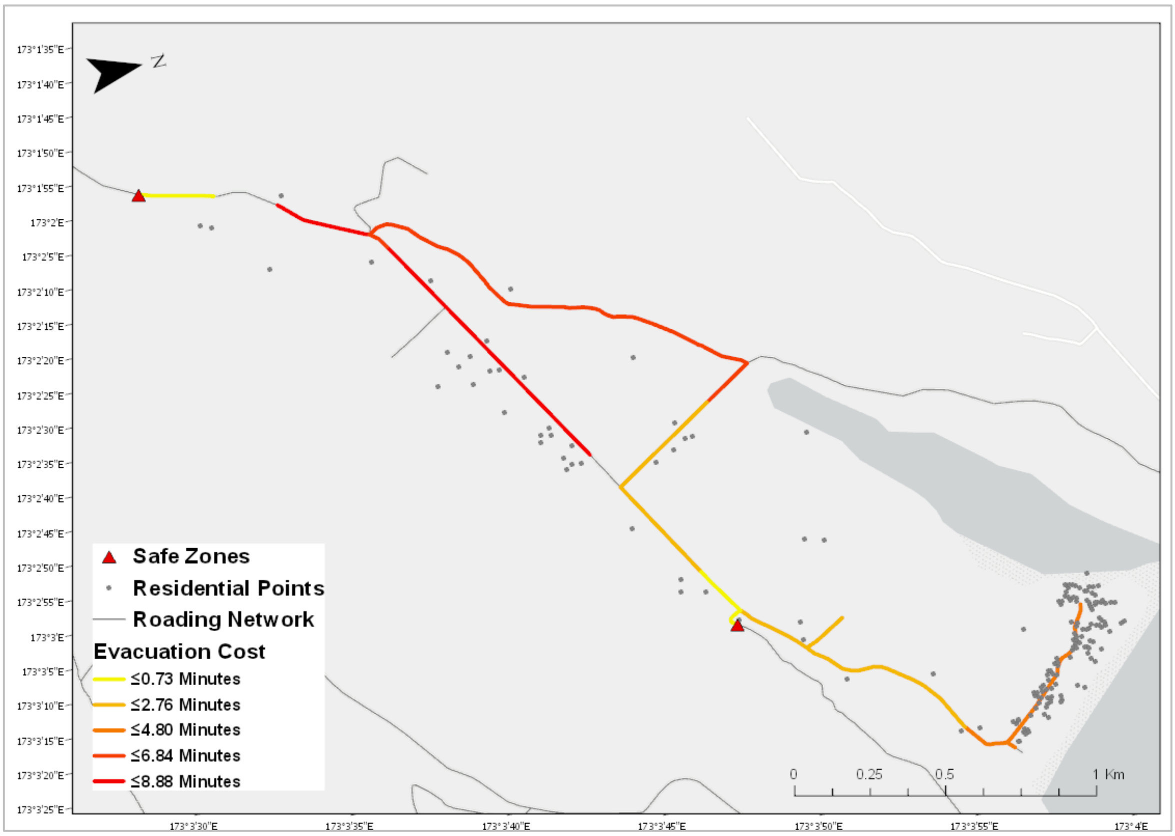

Figure 7.155: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

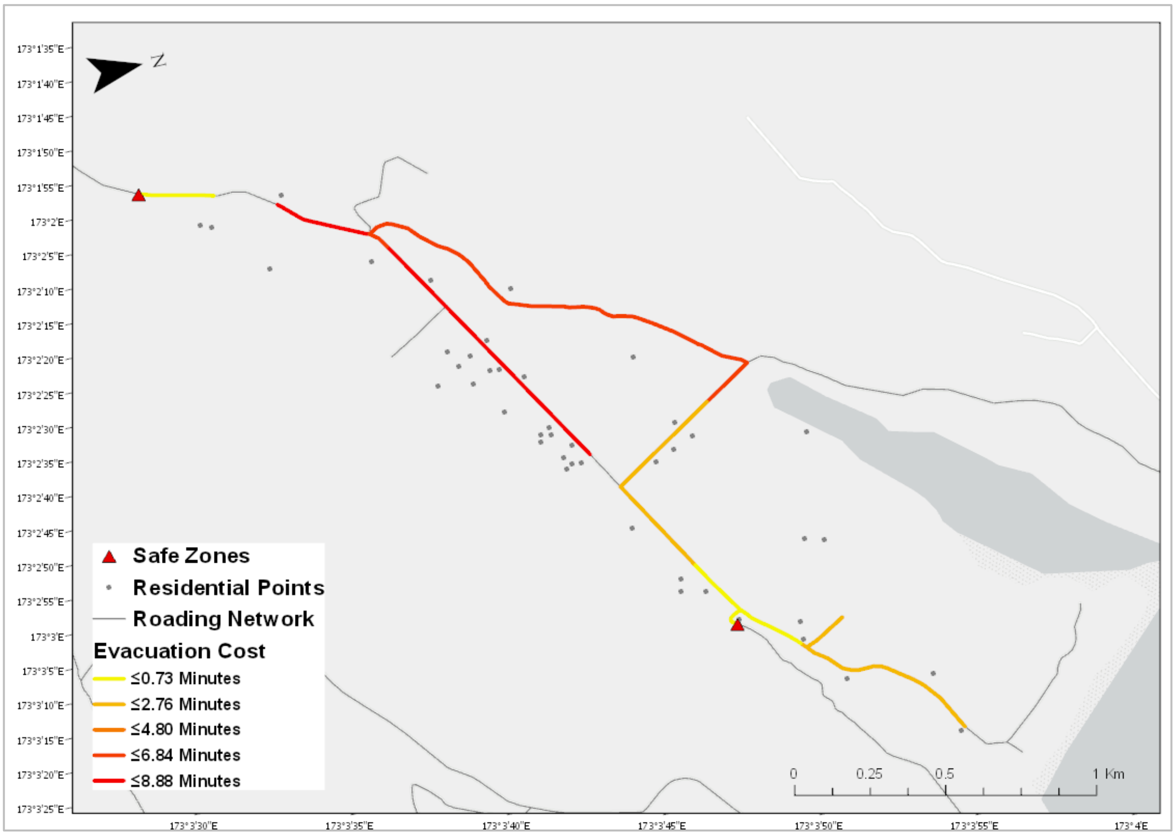

Figure 7.156: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

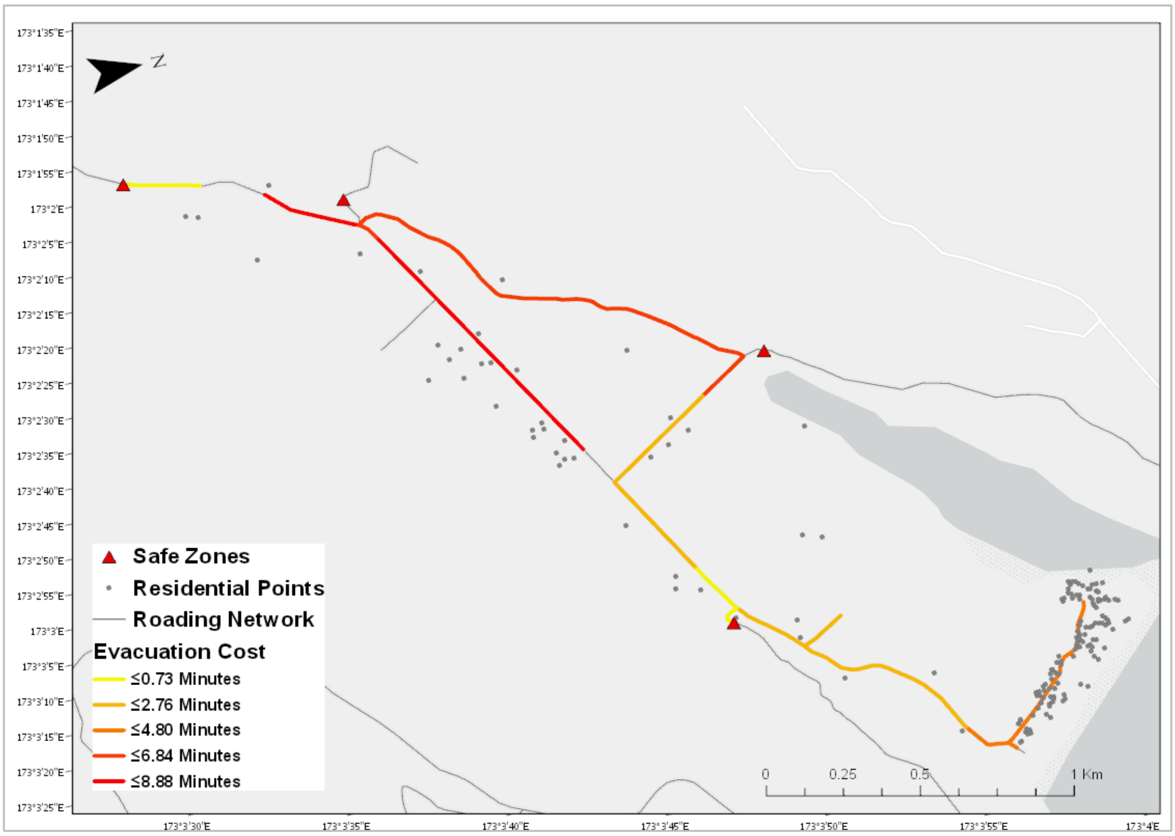

Figure 7.157: Evacuation cost results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

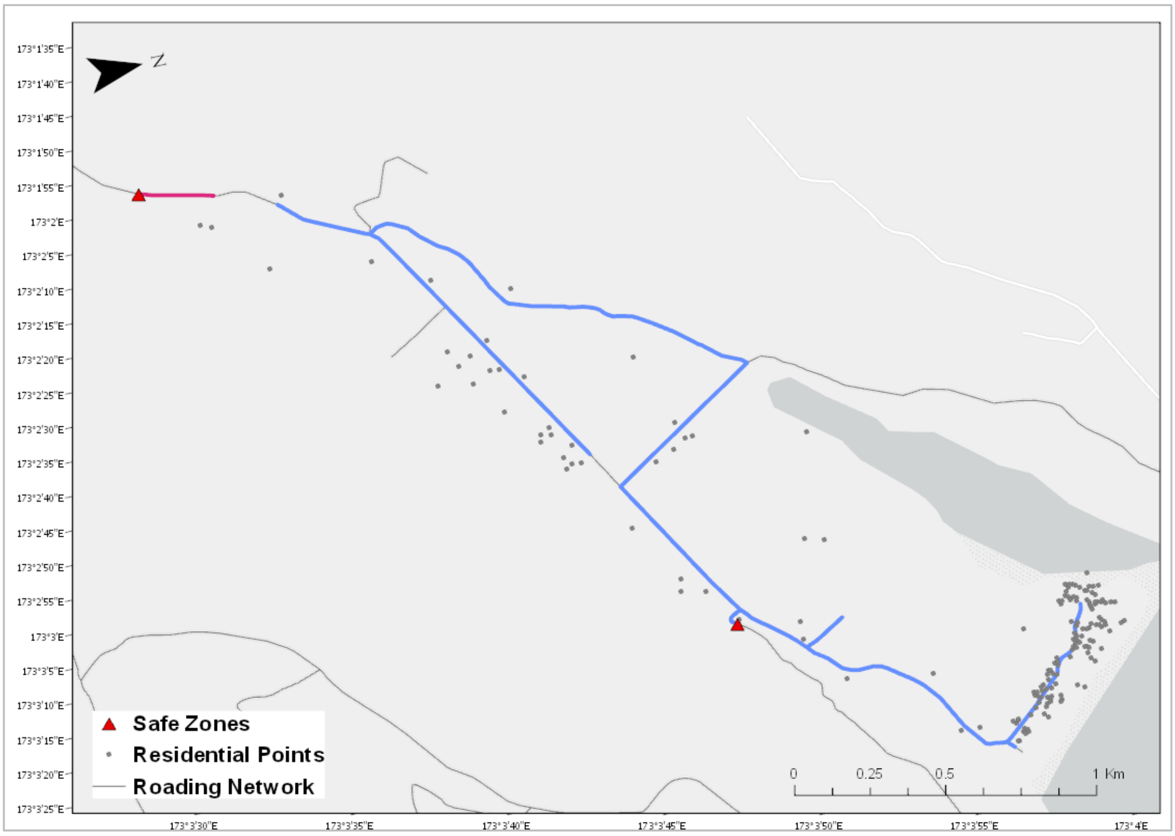

Figure 7.158: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

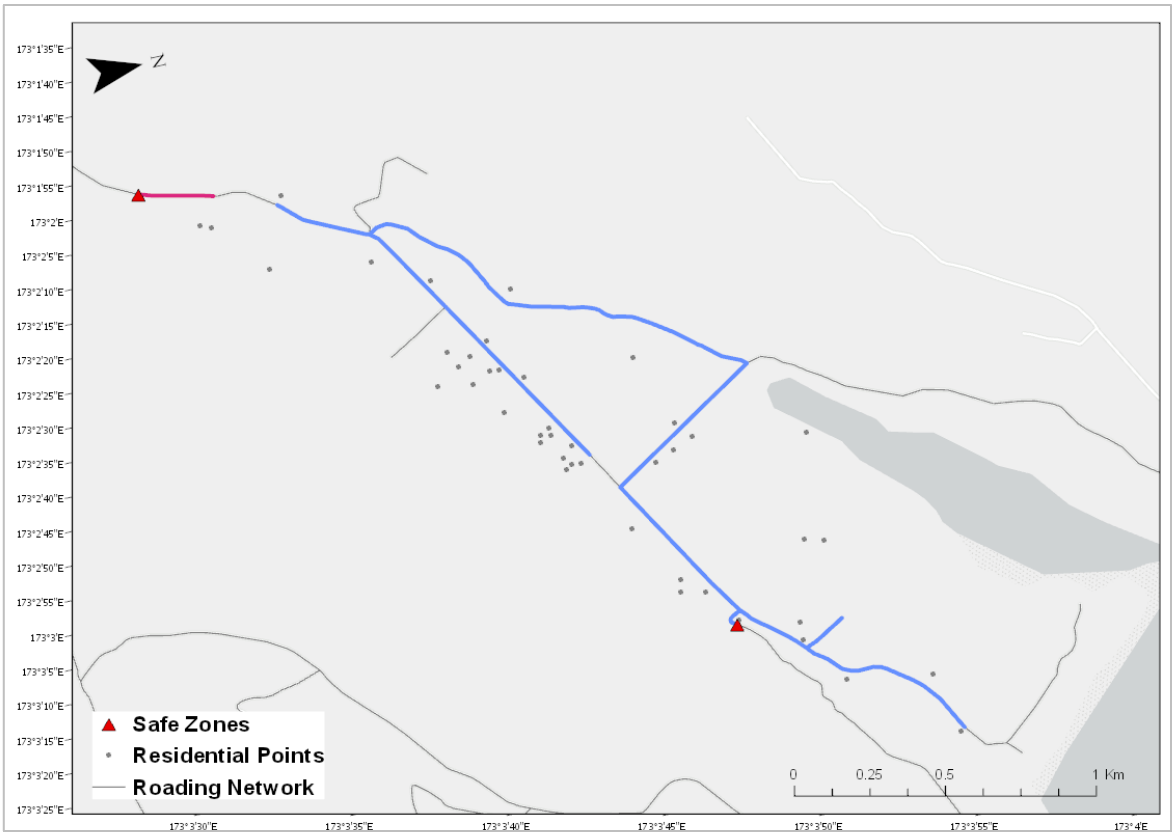

Figure 7.159: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

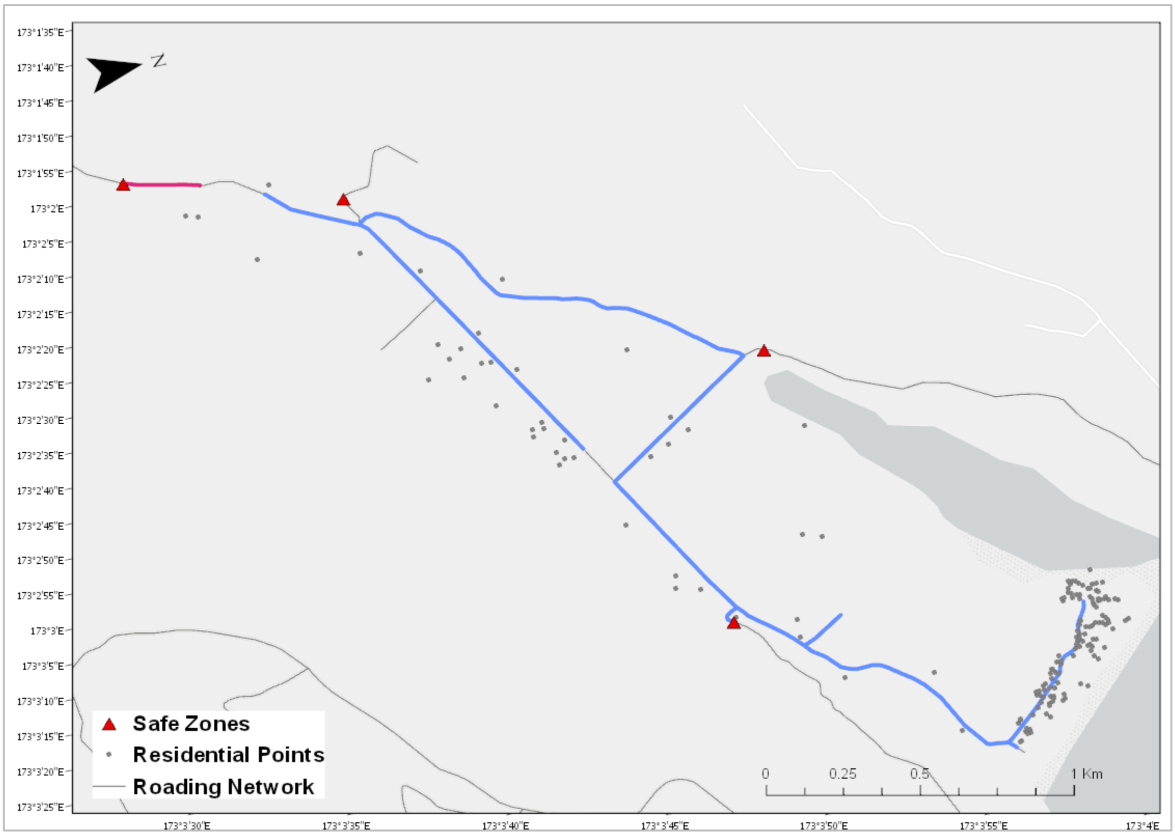

Figure 7.160: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

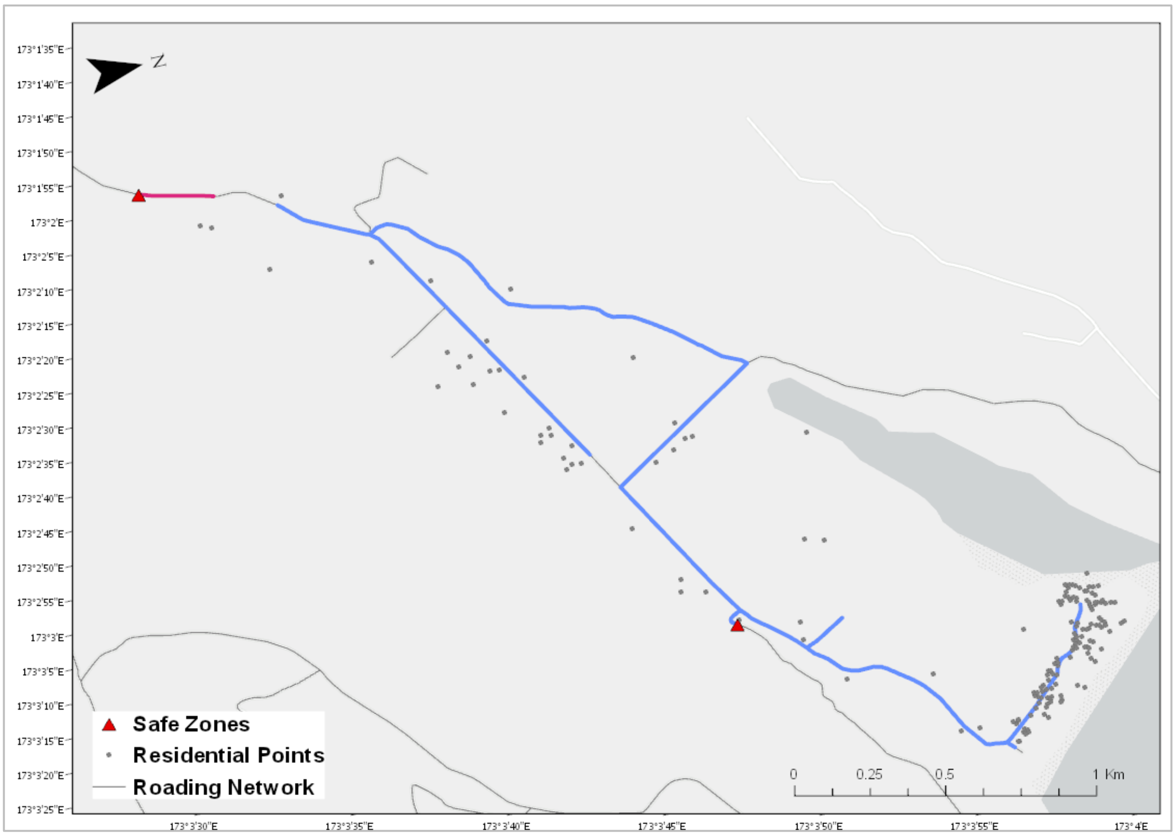

Figure 7.161: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

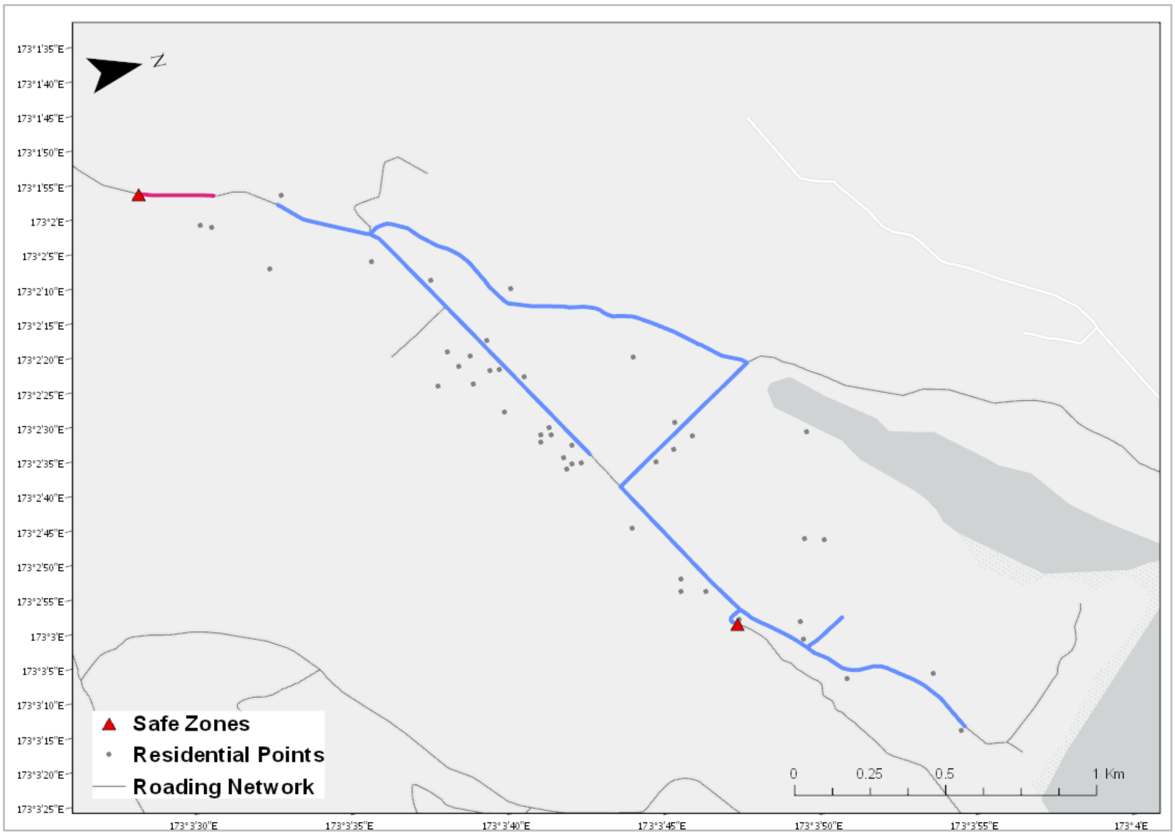

Figure 7.162: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

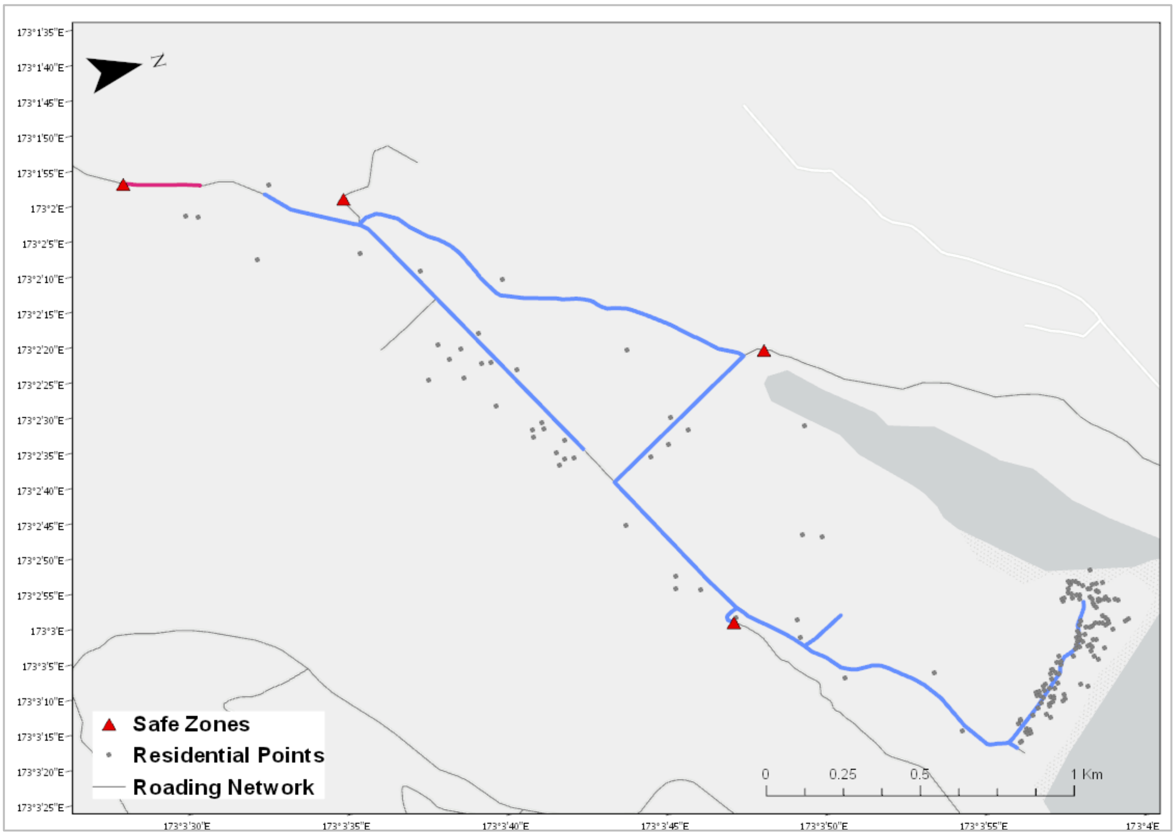

Figure 7.163: Safe zone distribution results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

g. Pigeon Bay

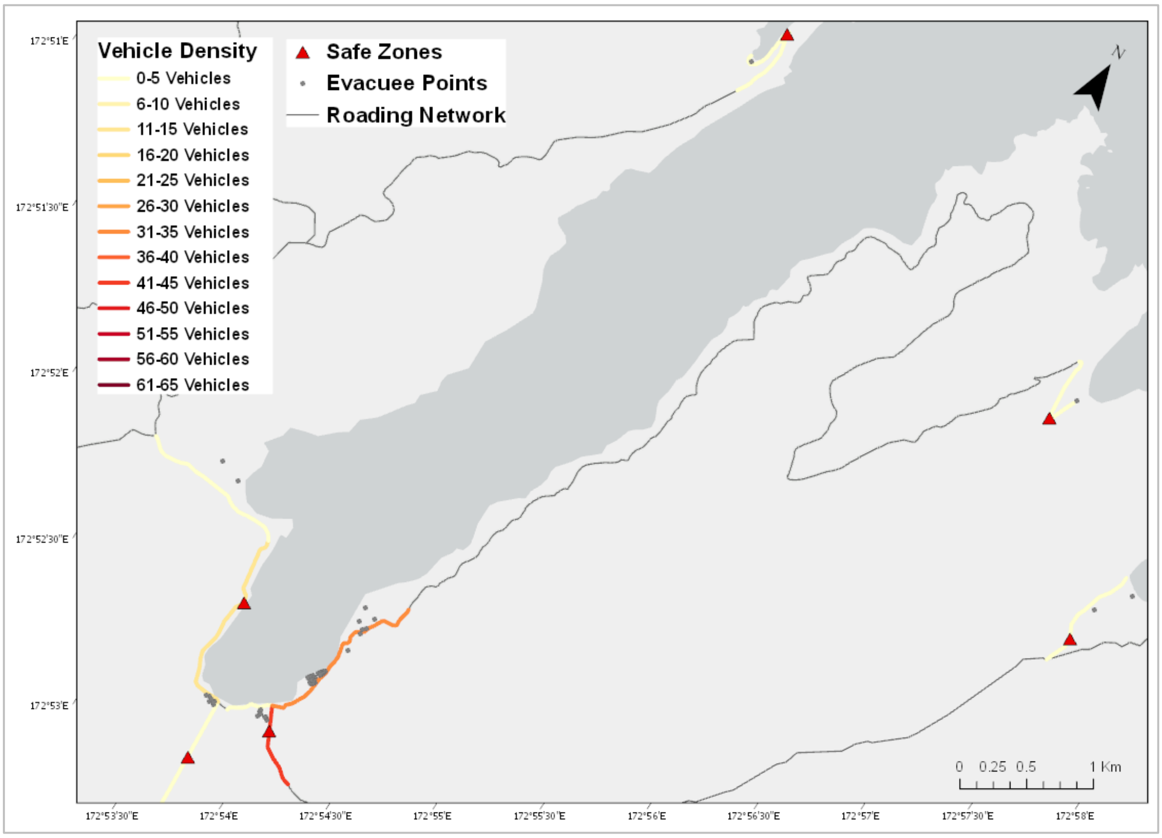

Figure 7.164: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

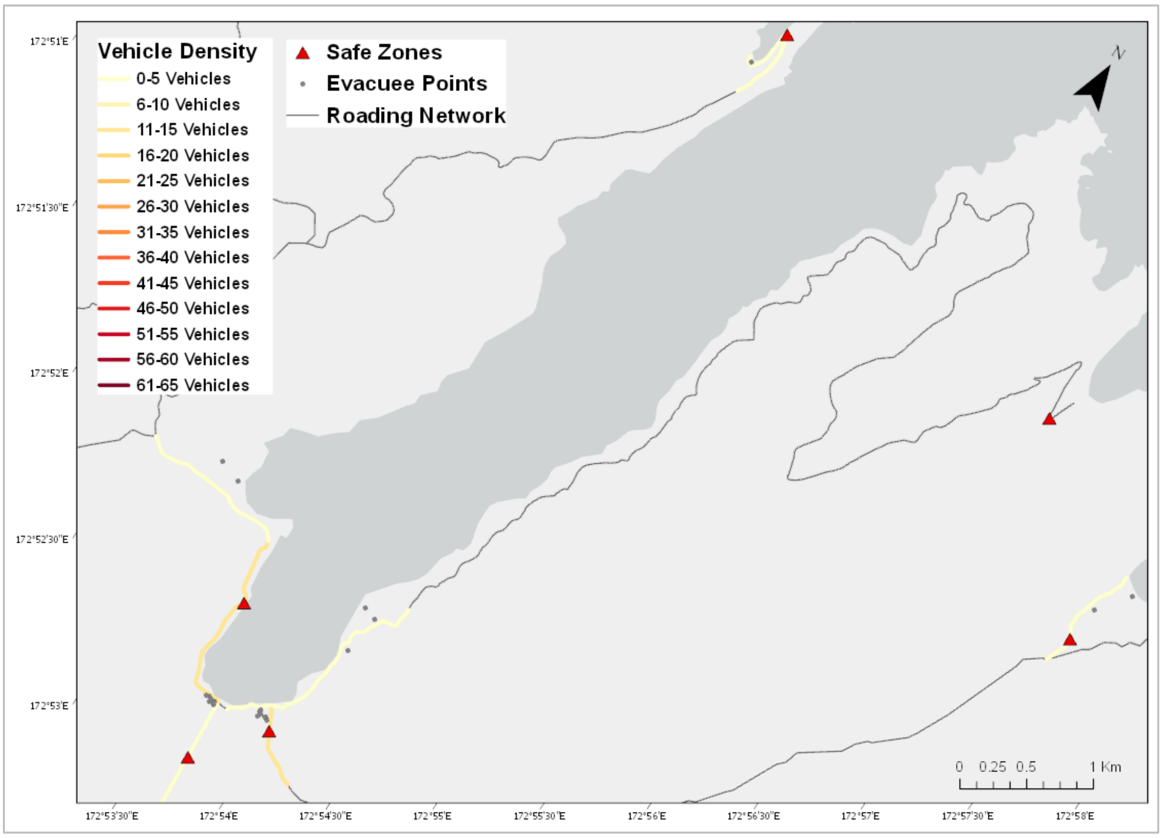

Figure 7.165: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

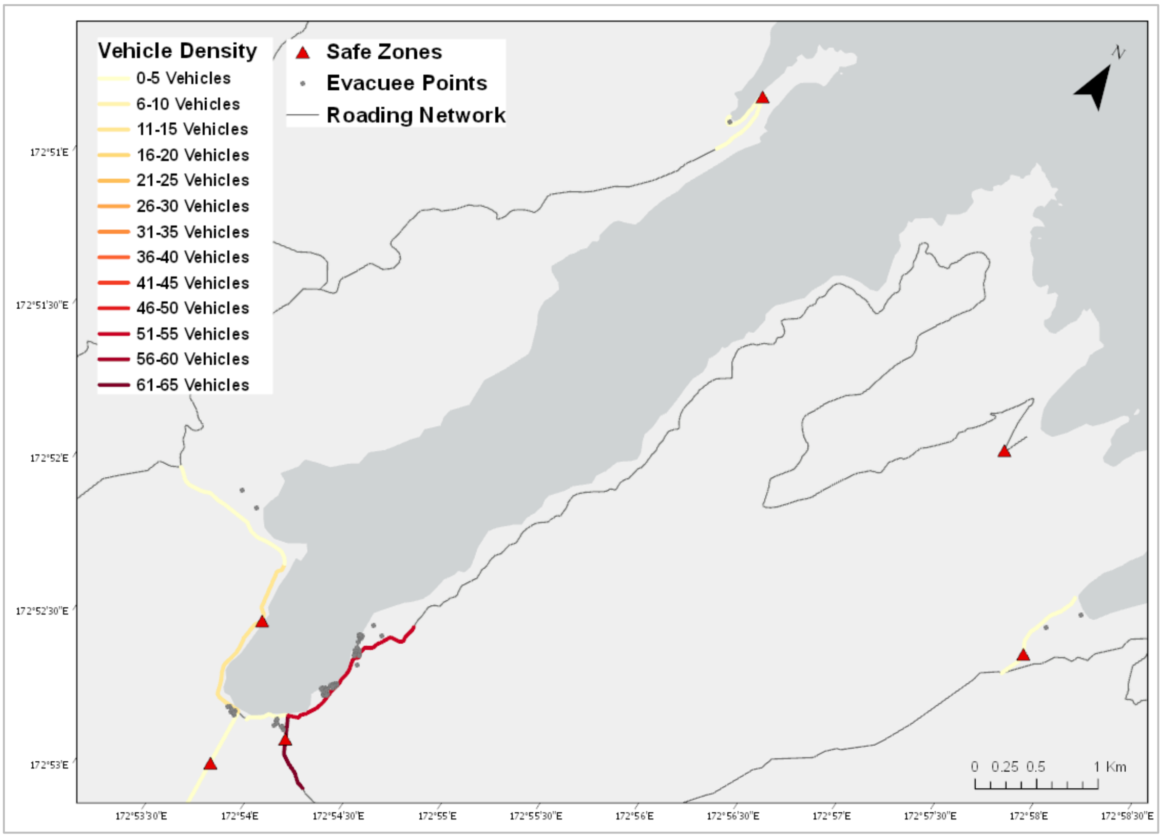

Figure 7.166: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

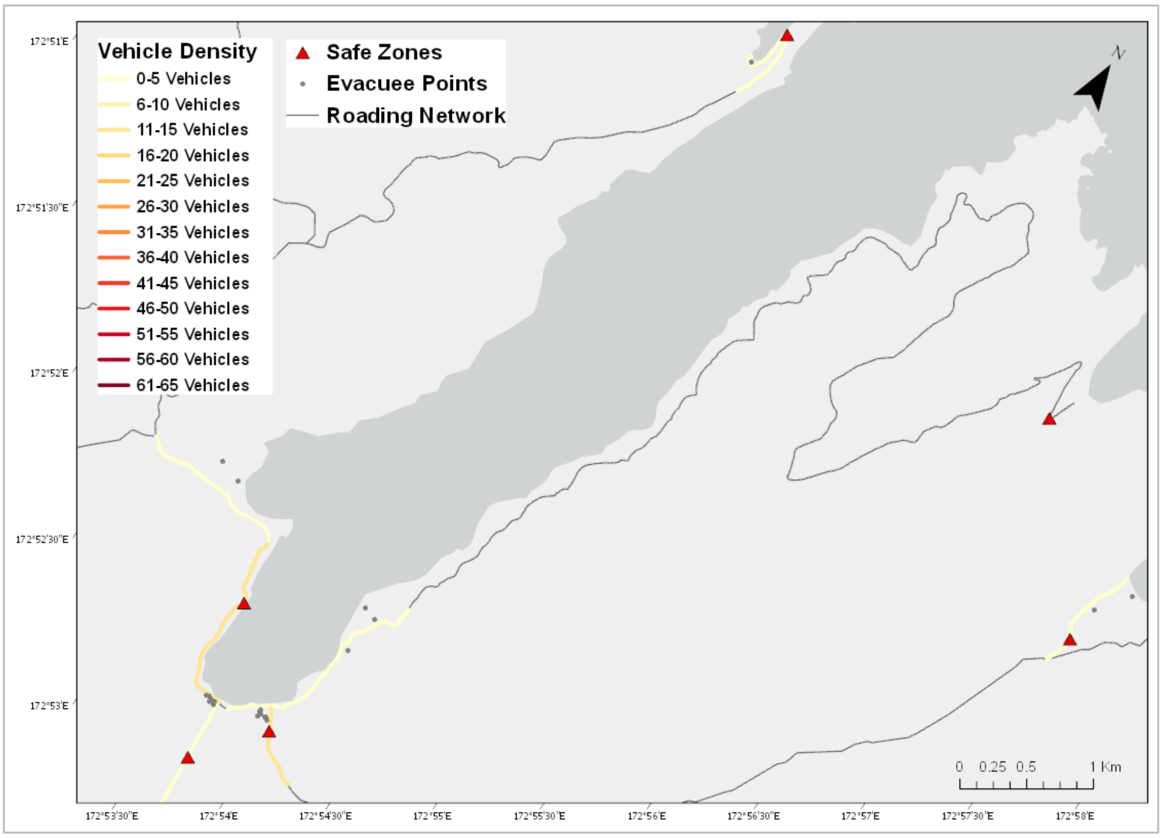

Figure 7.167: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

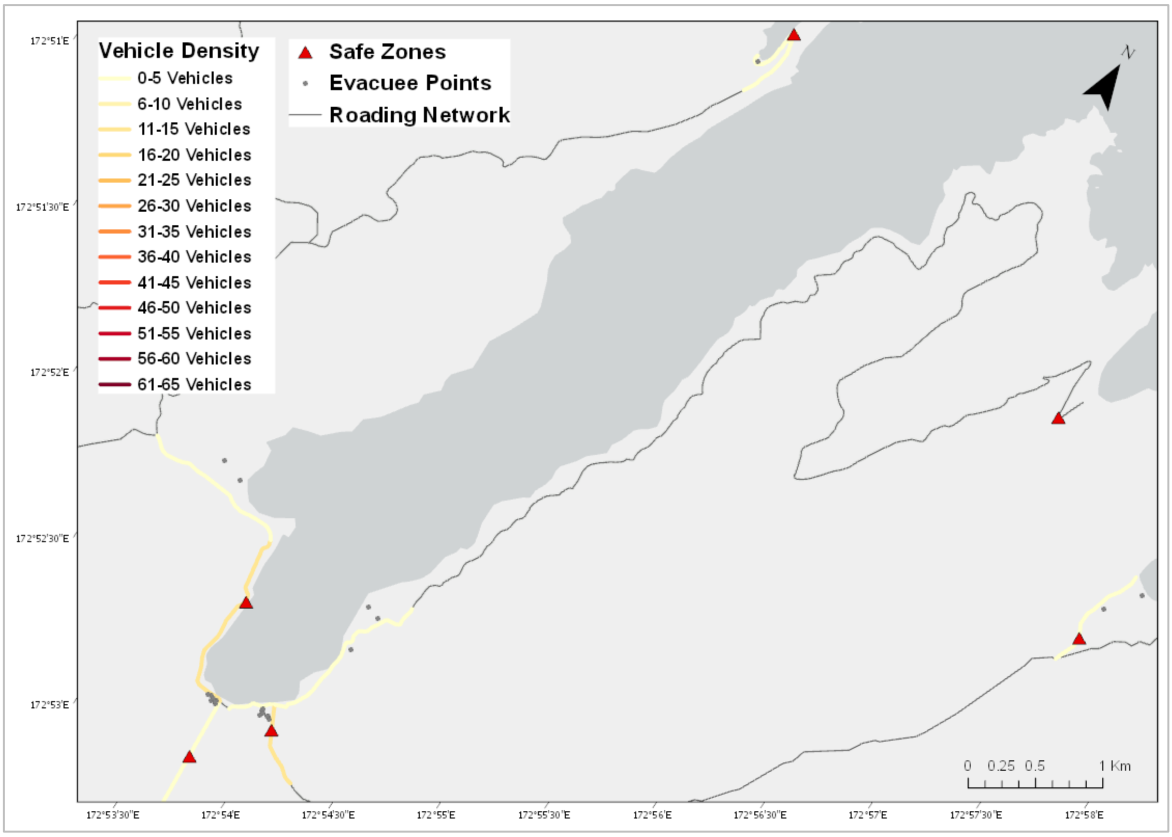

Figure 7.168: Vehicle density count results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

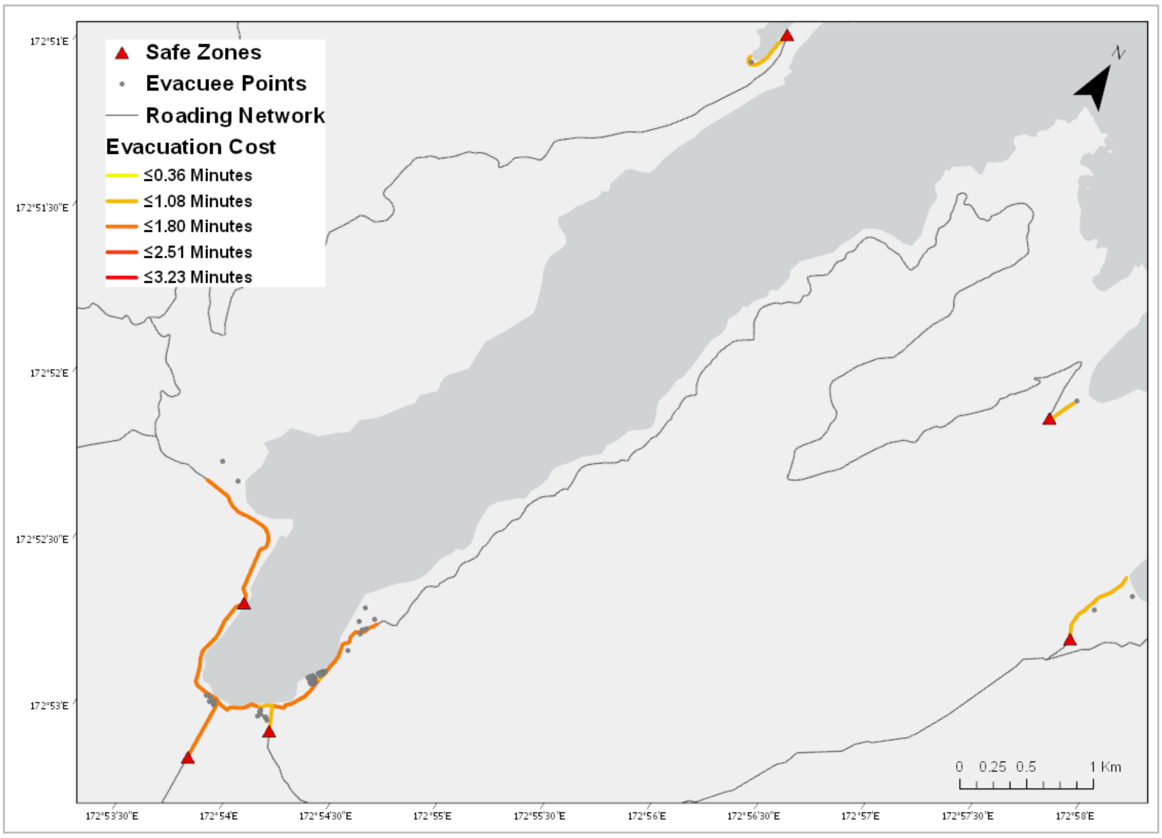

Figure 7.169: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

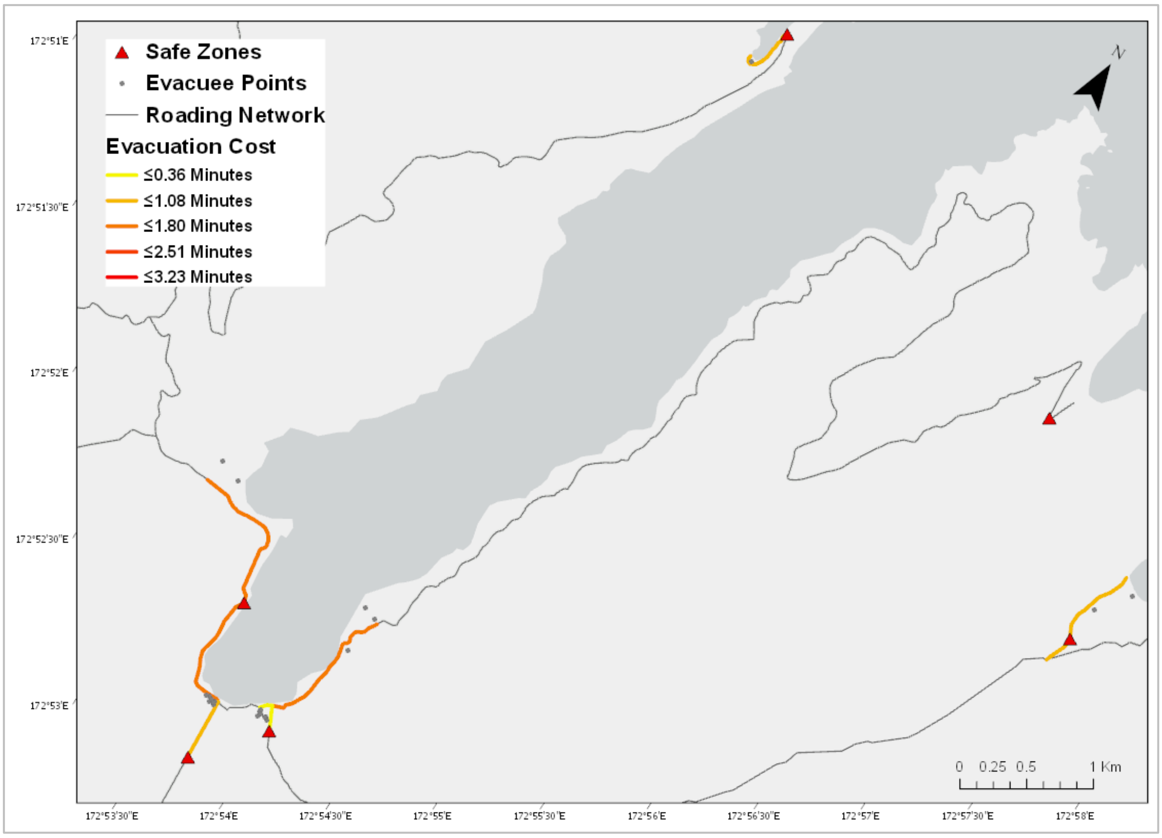

Figure 7.170: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

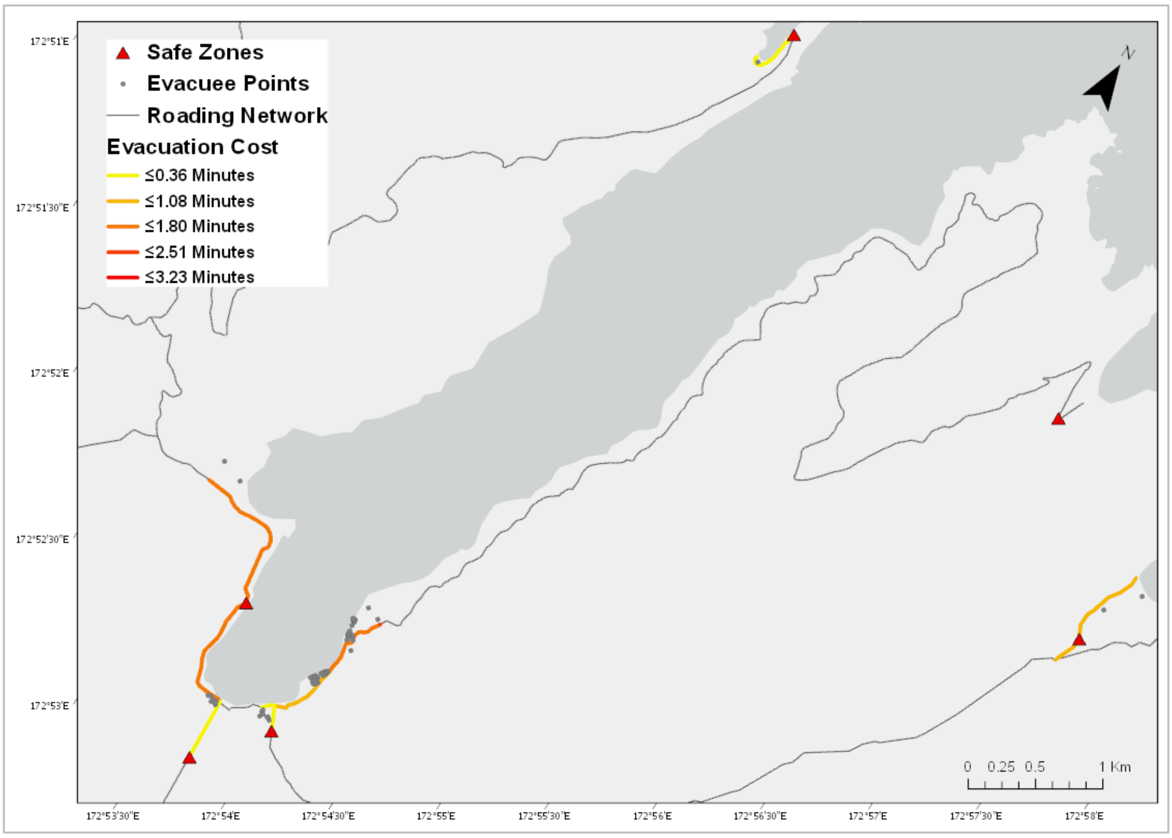

Figure 7.171: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

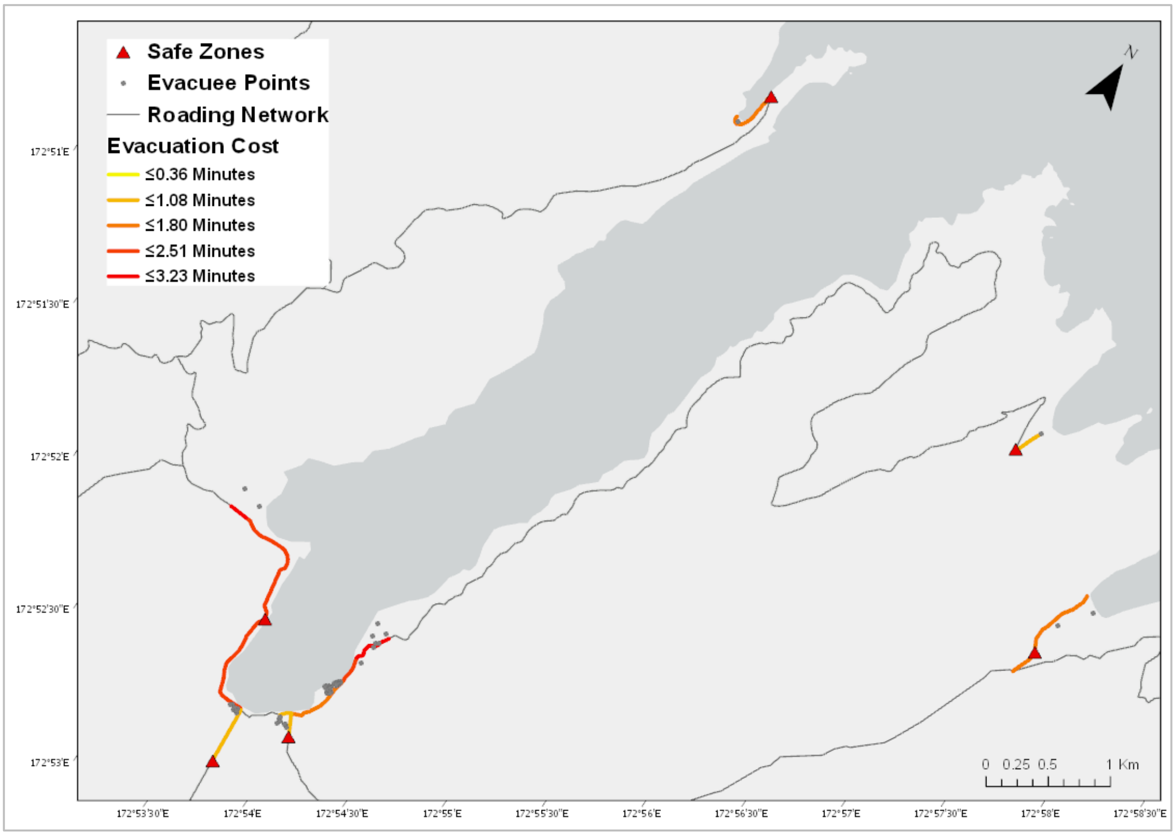

Figure 7.172: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

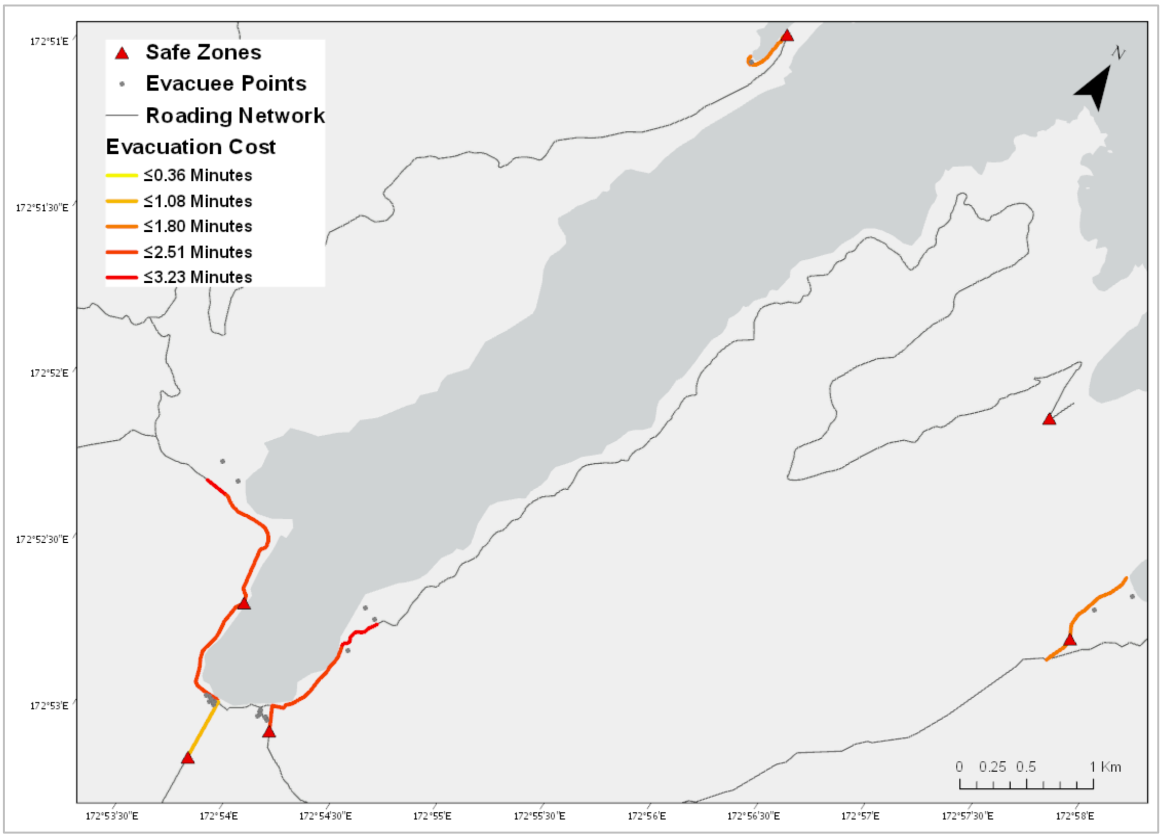

Figure 7.173: Evacuation cost results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

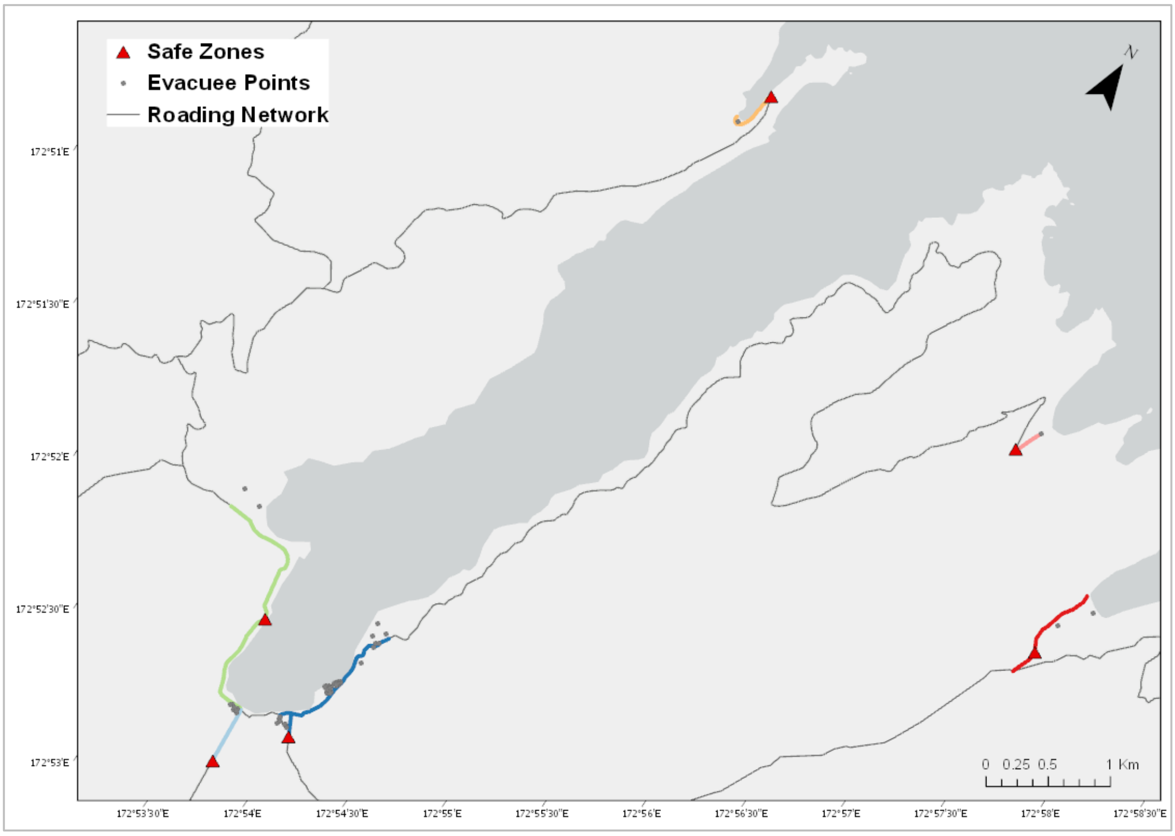

Figure 7.174: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

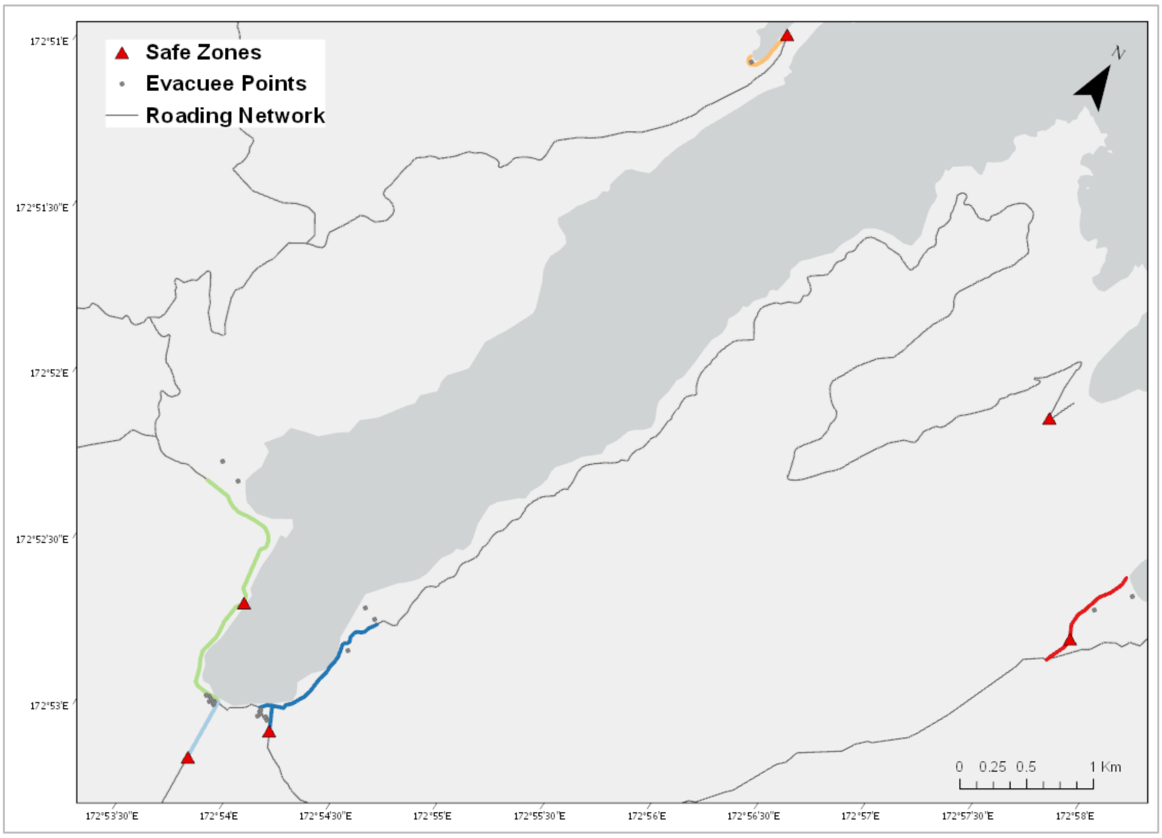

Figure 7.175: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

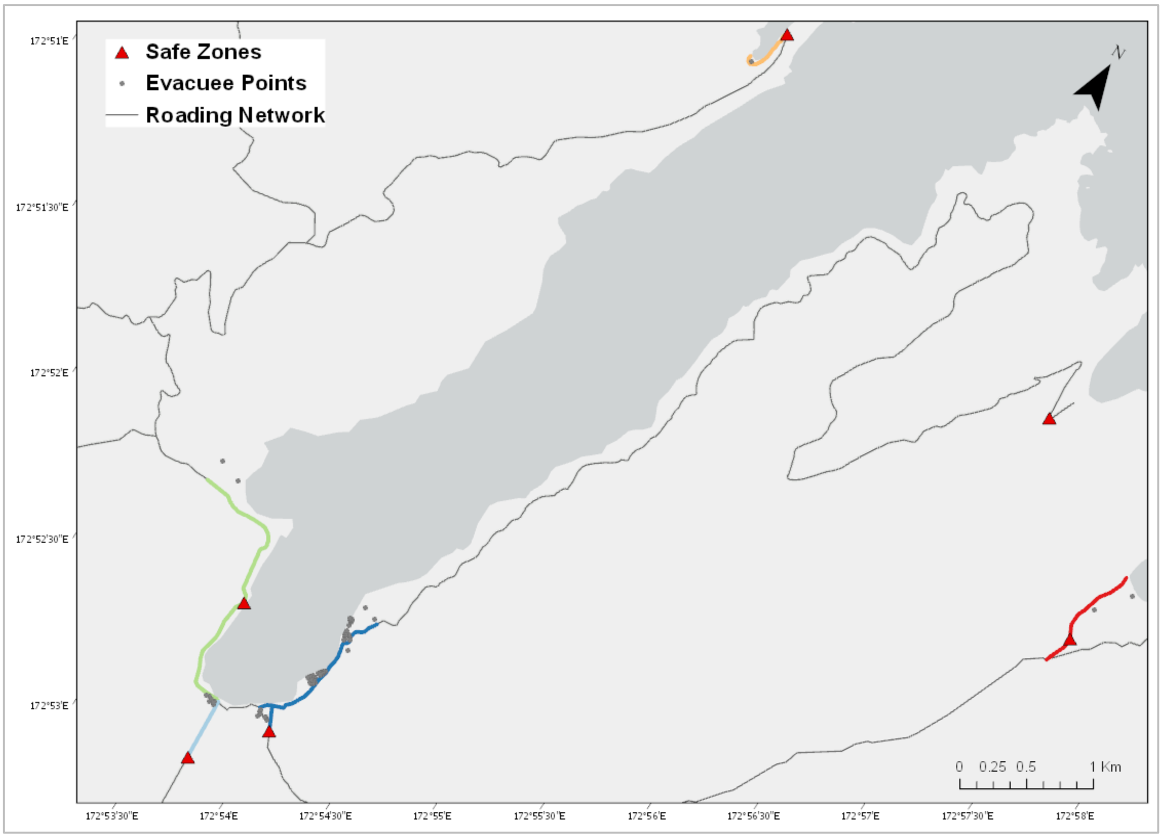

Figure 7.176: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

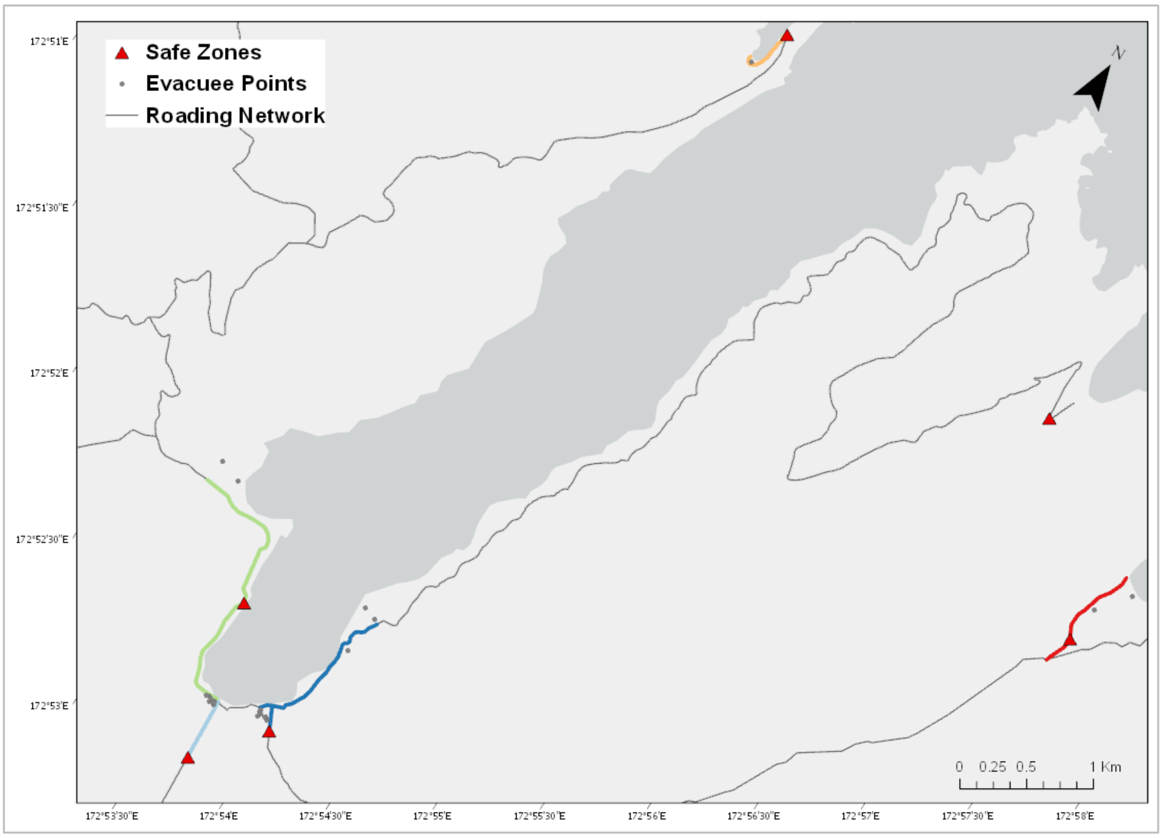

Figure 7.177: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

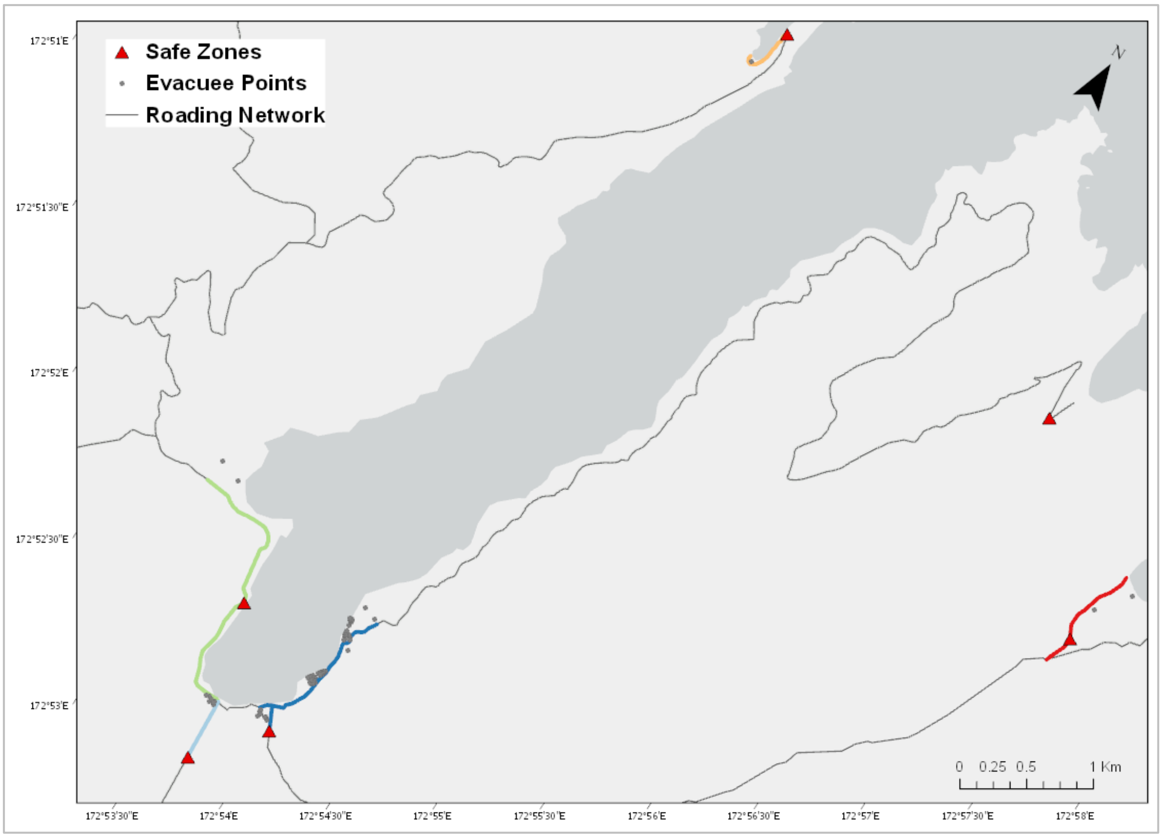

Figure 7.178: Safe zone distribution results for Pigeon Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

h. Takamatua Bay and Robinsons Bay

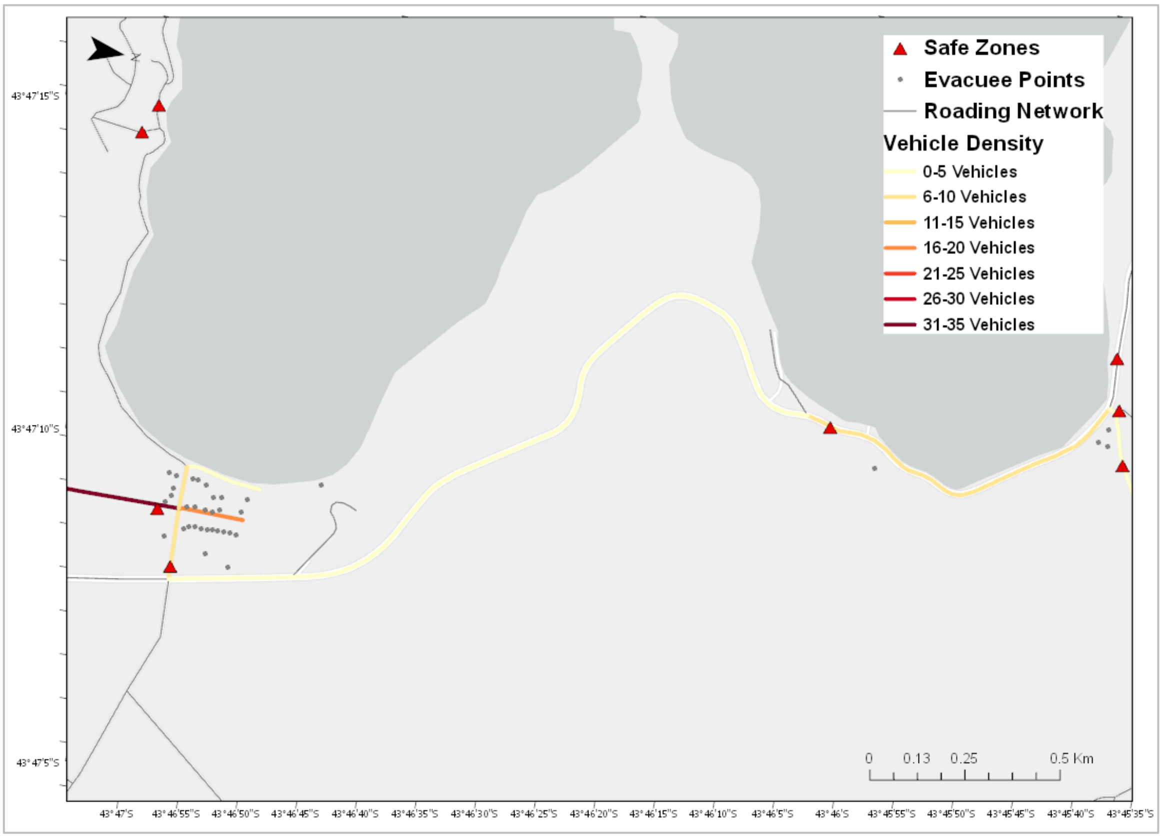

Figure 7.179: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

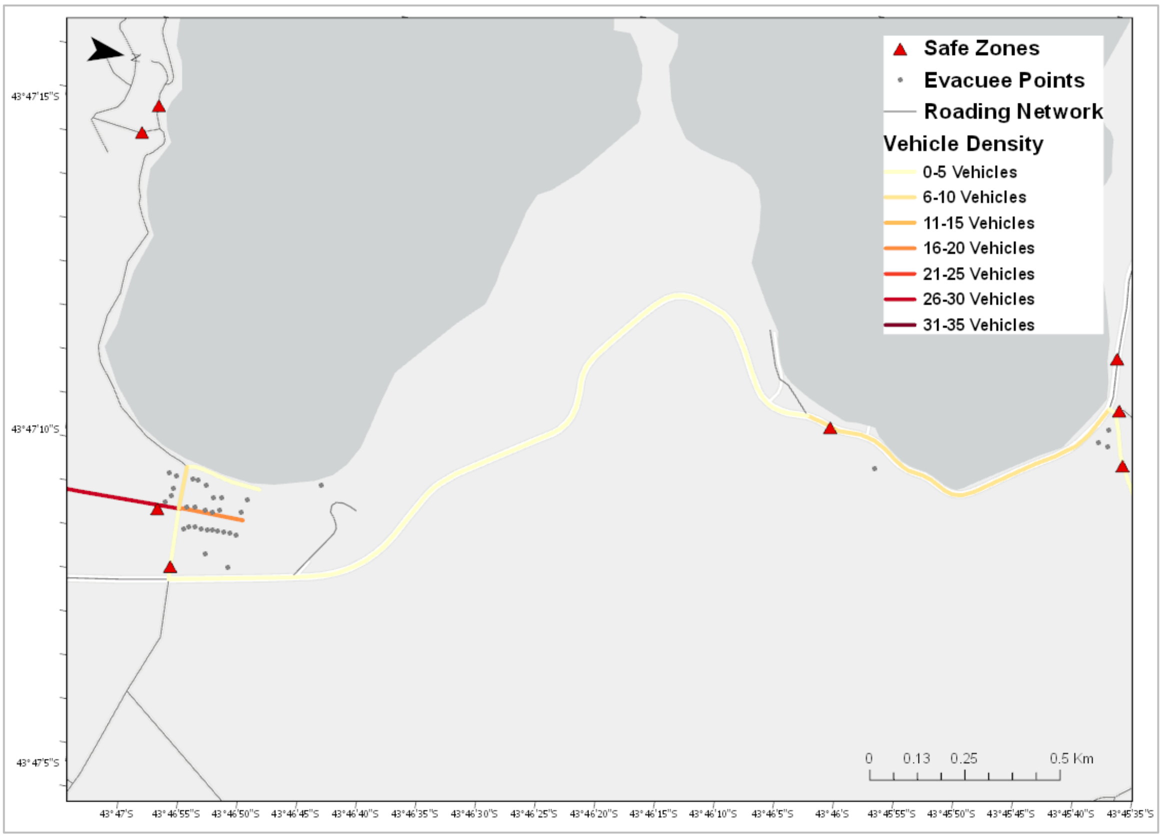

Figure 7.180: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

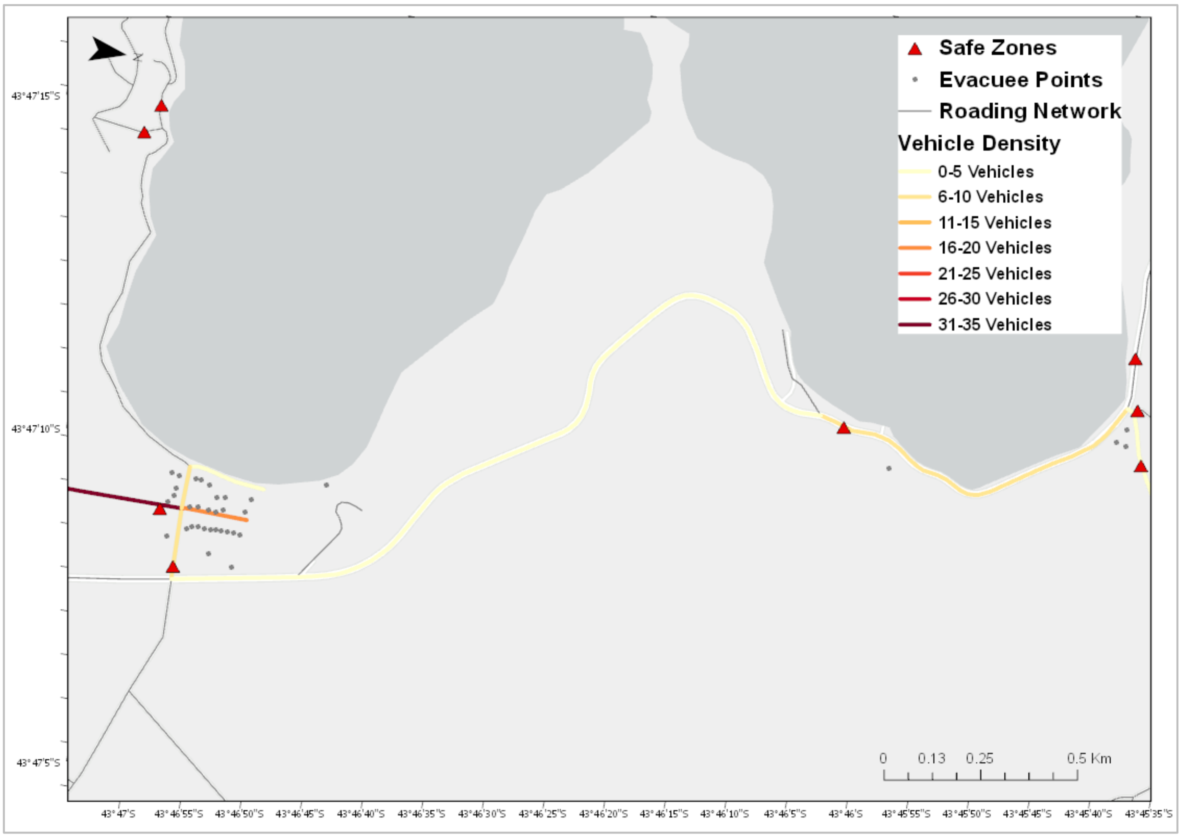

Figure 7.181: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

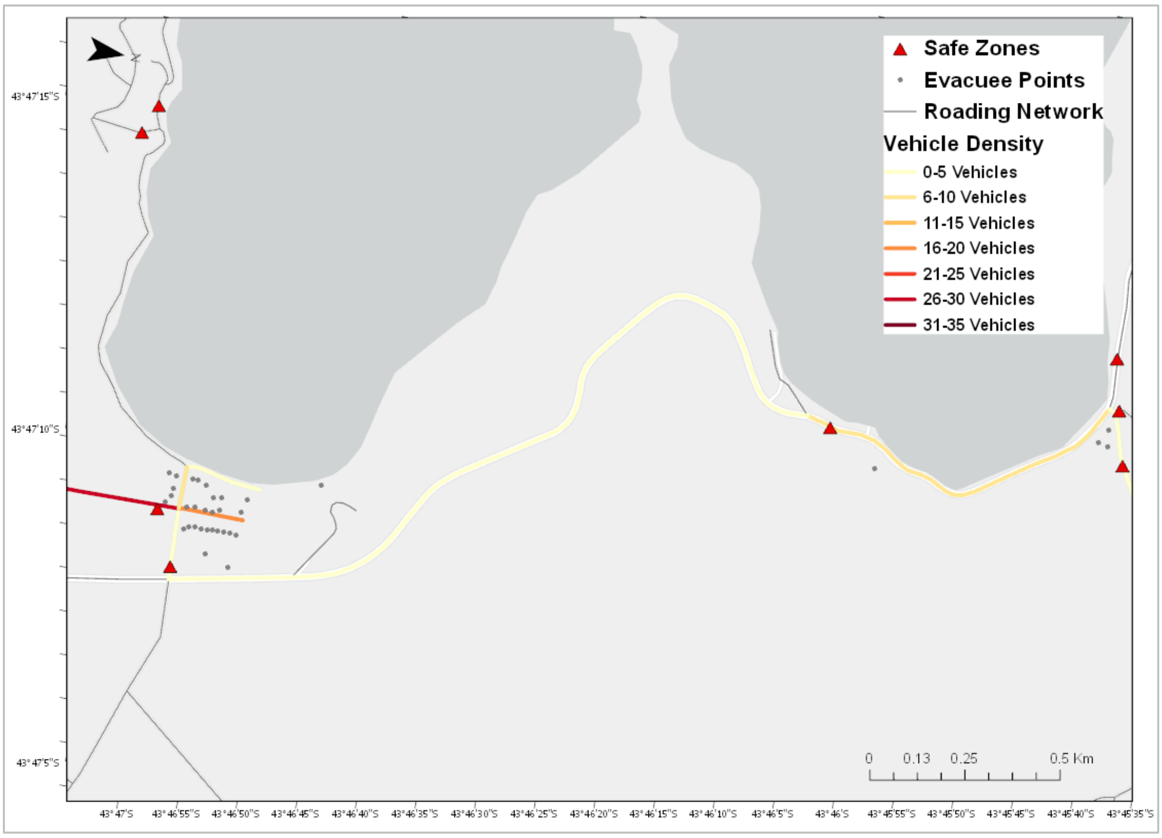

Figure 7.182: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

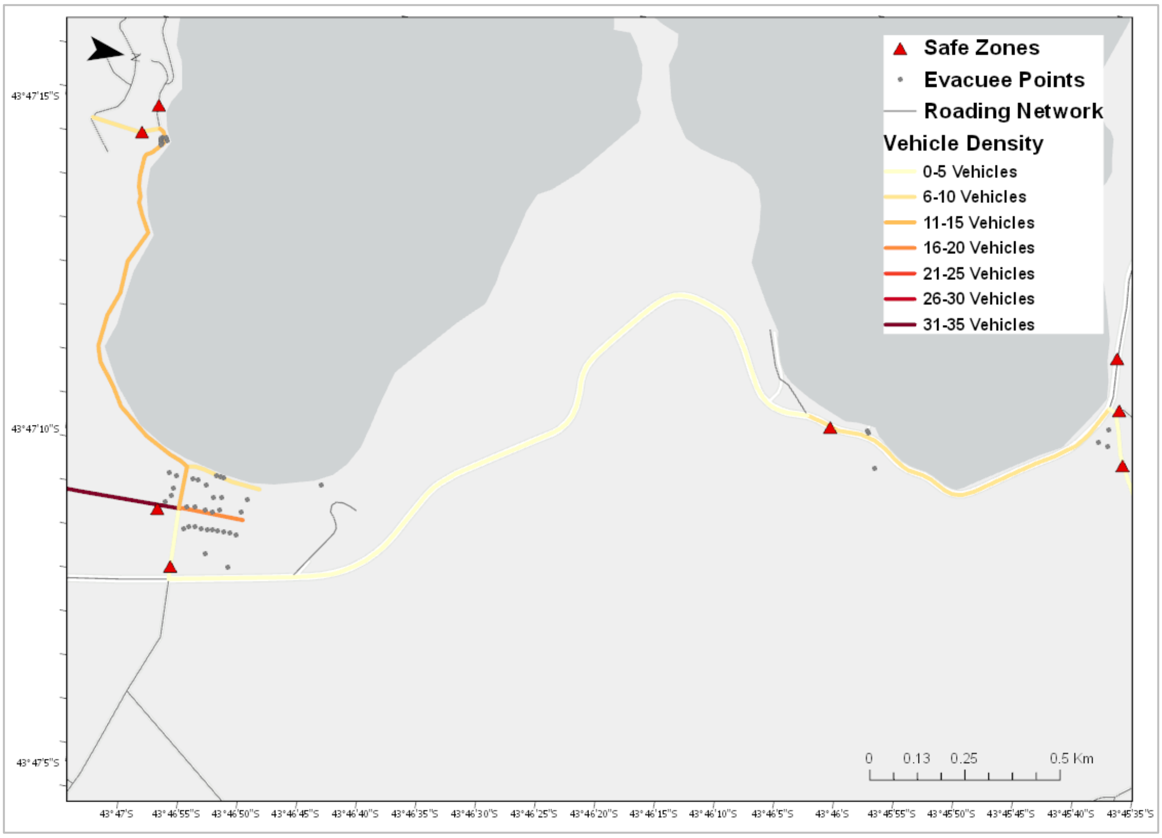

Figure 7.183: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario

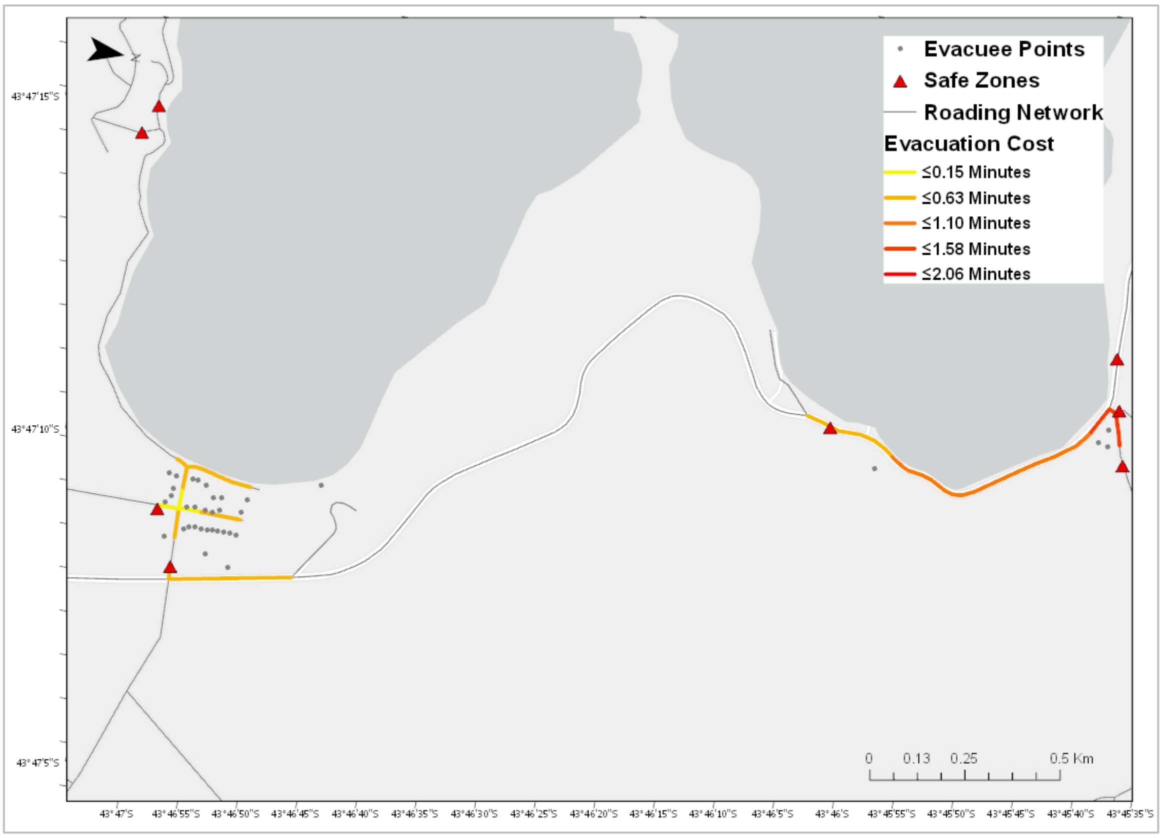

Figure 7.184: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

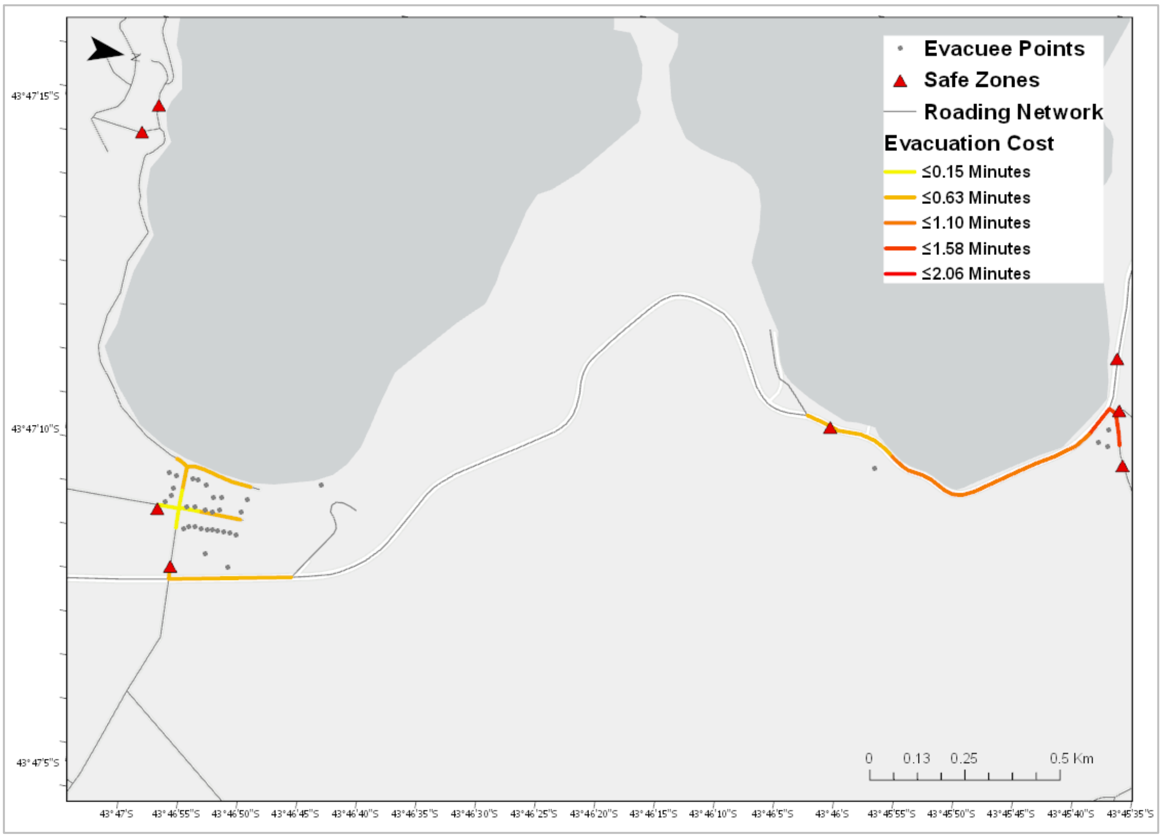

Figure 7.185: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

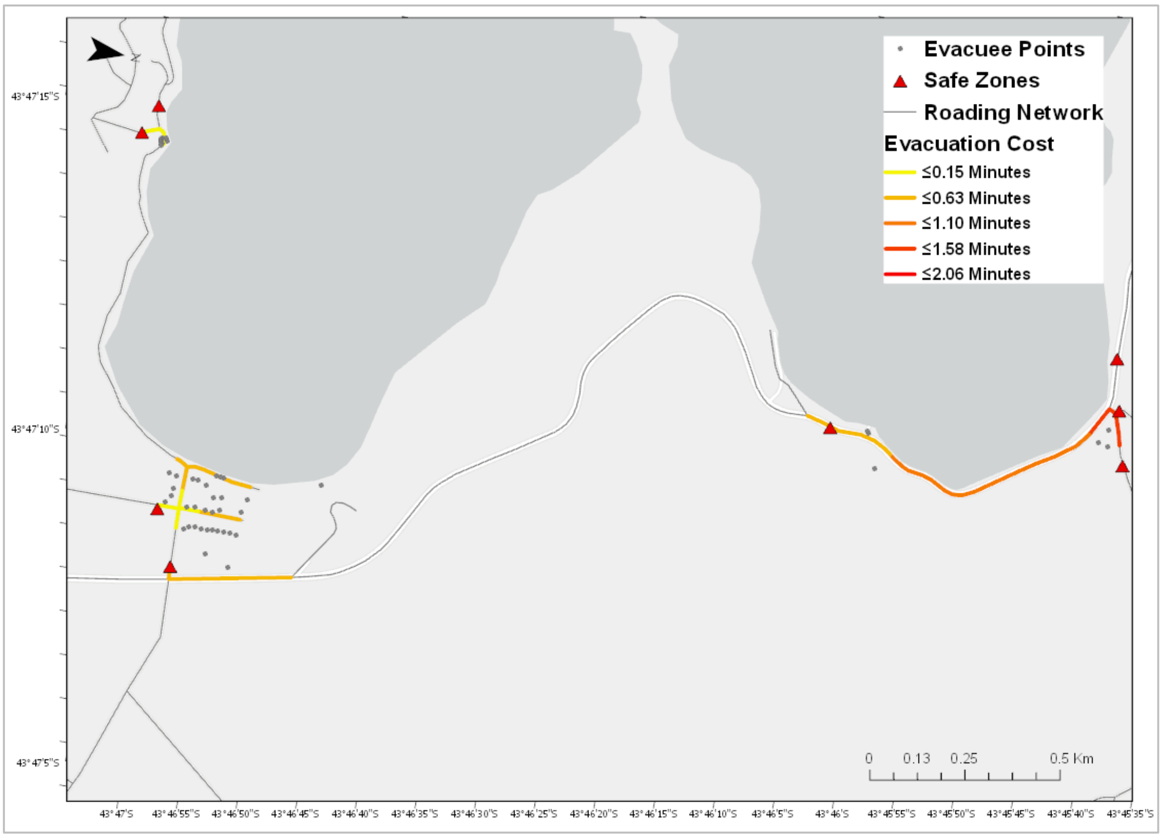

Figure 7.186: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

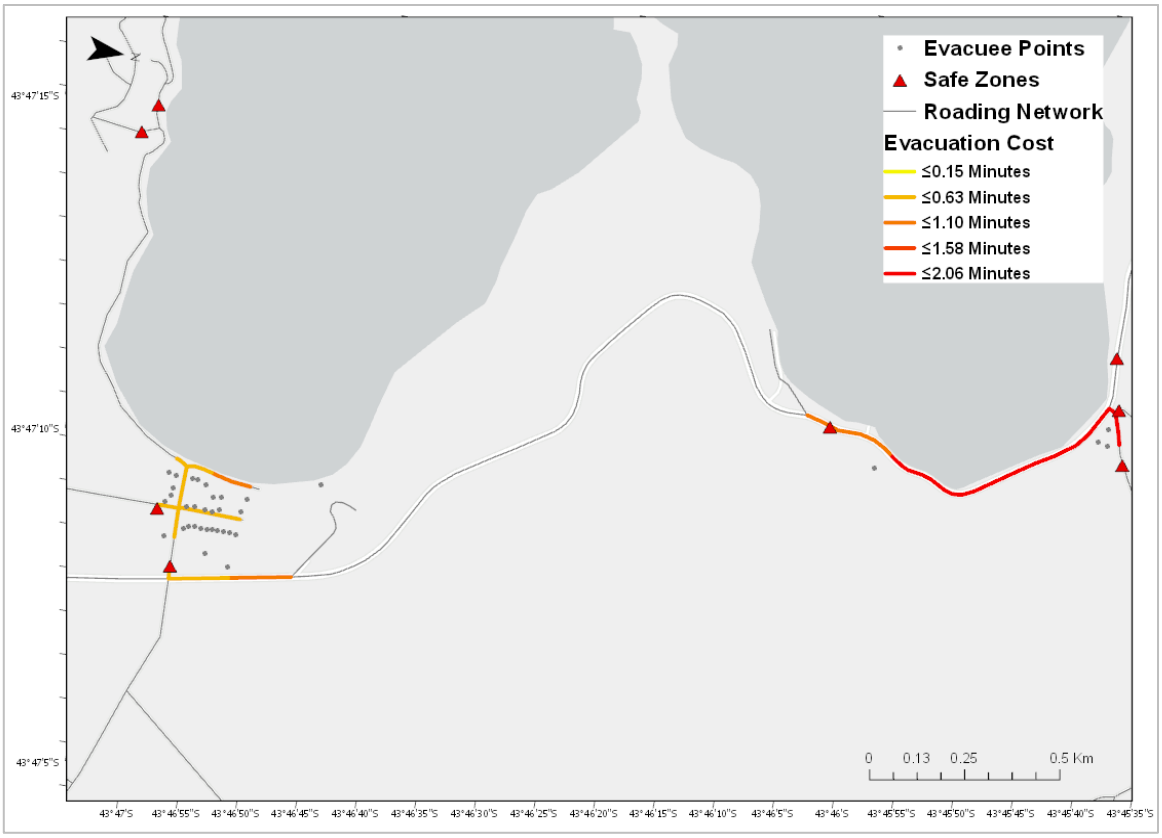

Figure 7.187: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario

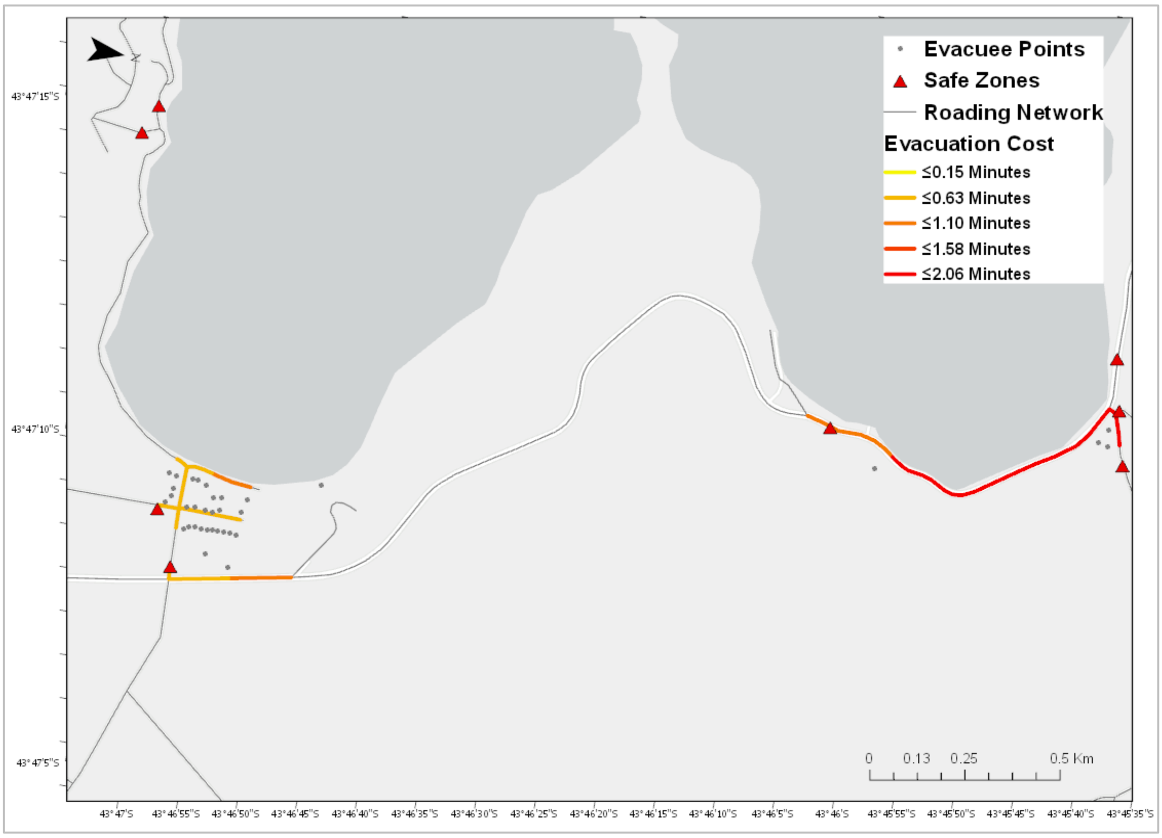

Figure 7.188: Vehicle density count results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

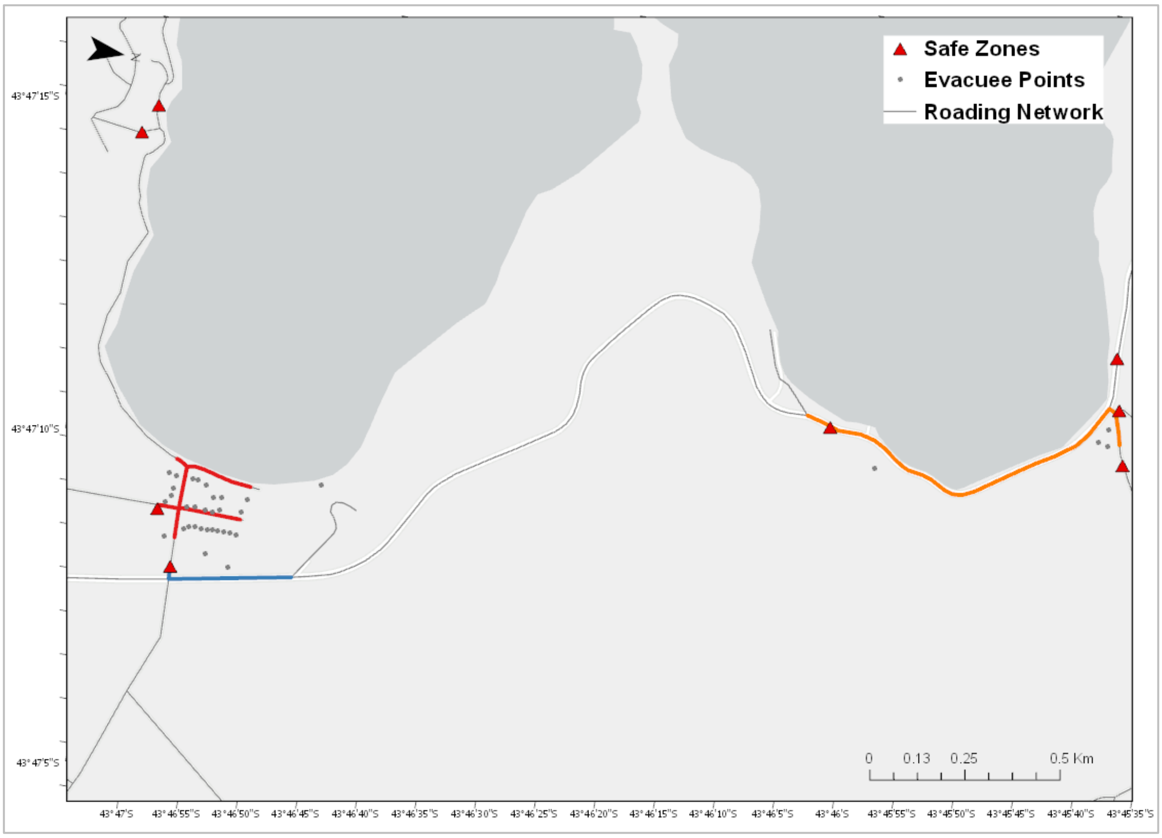

Figure 7.189: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak night traffic scenario.

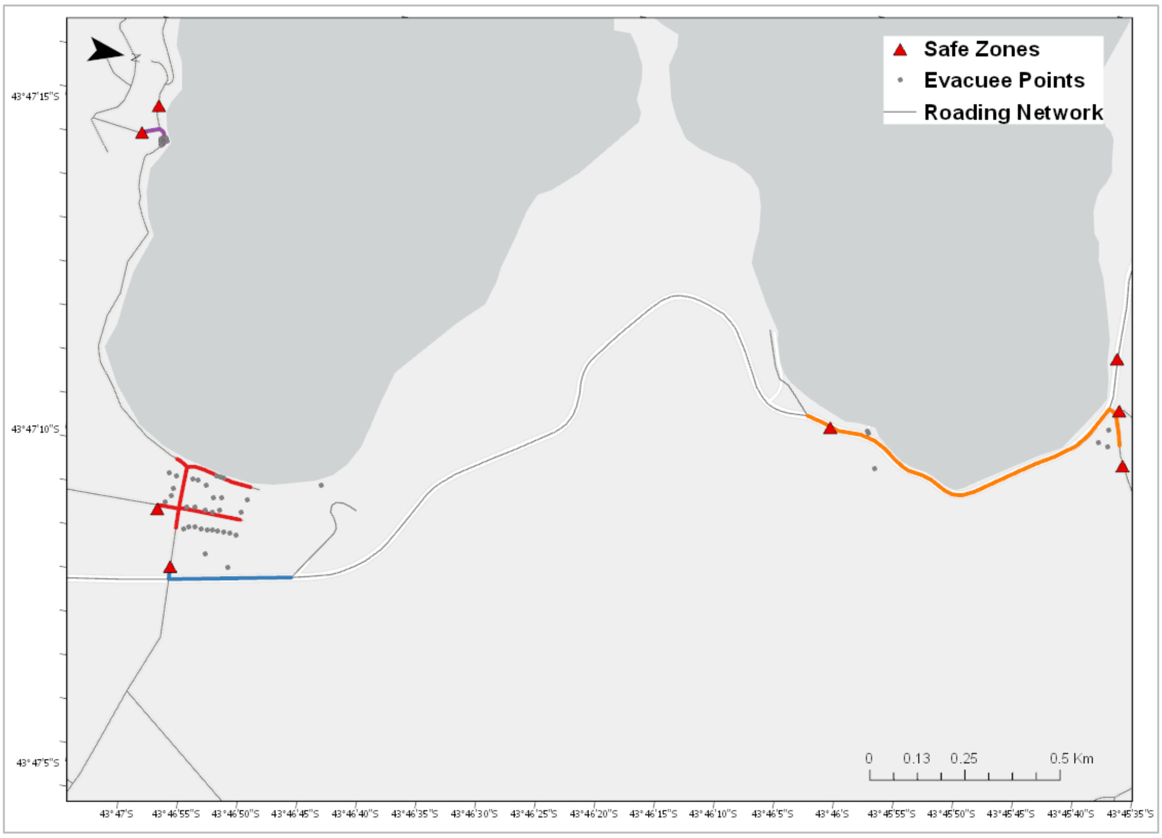

Figure 7.190: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

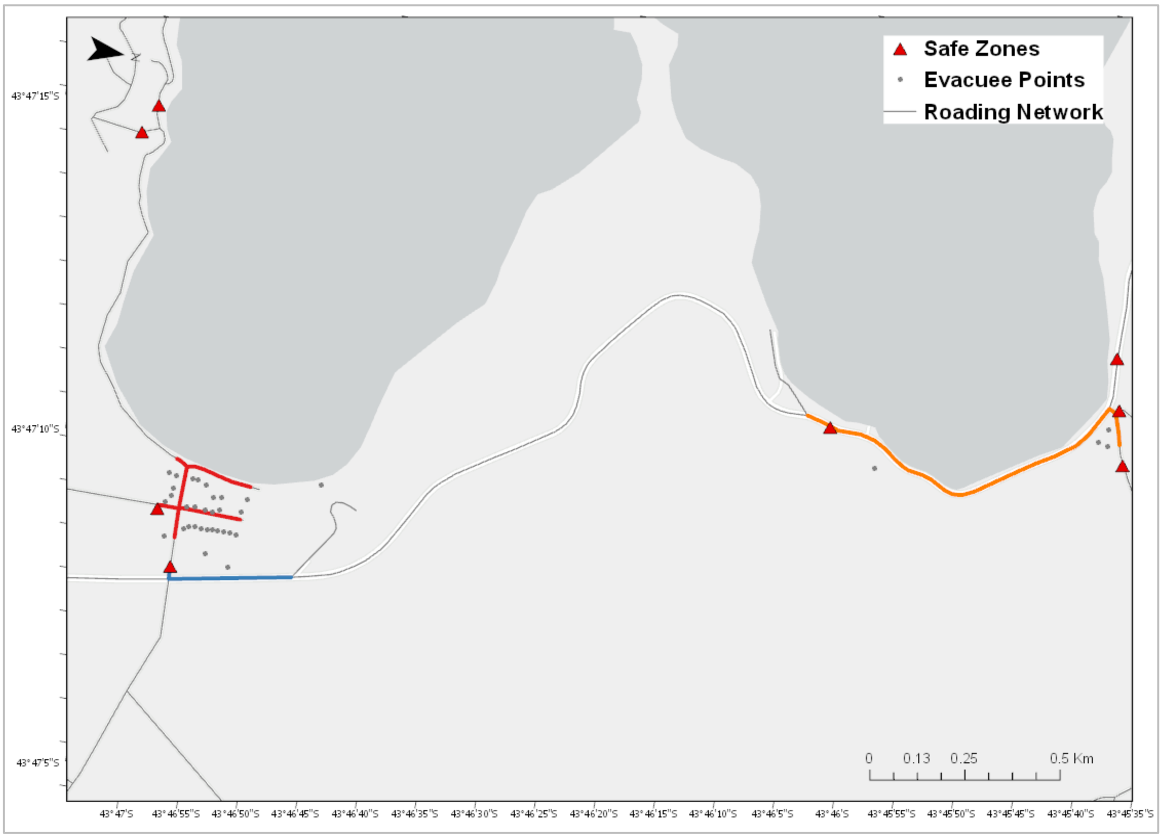

Figure 7.191: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak night traffic scenario.

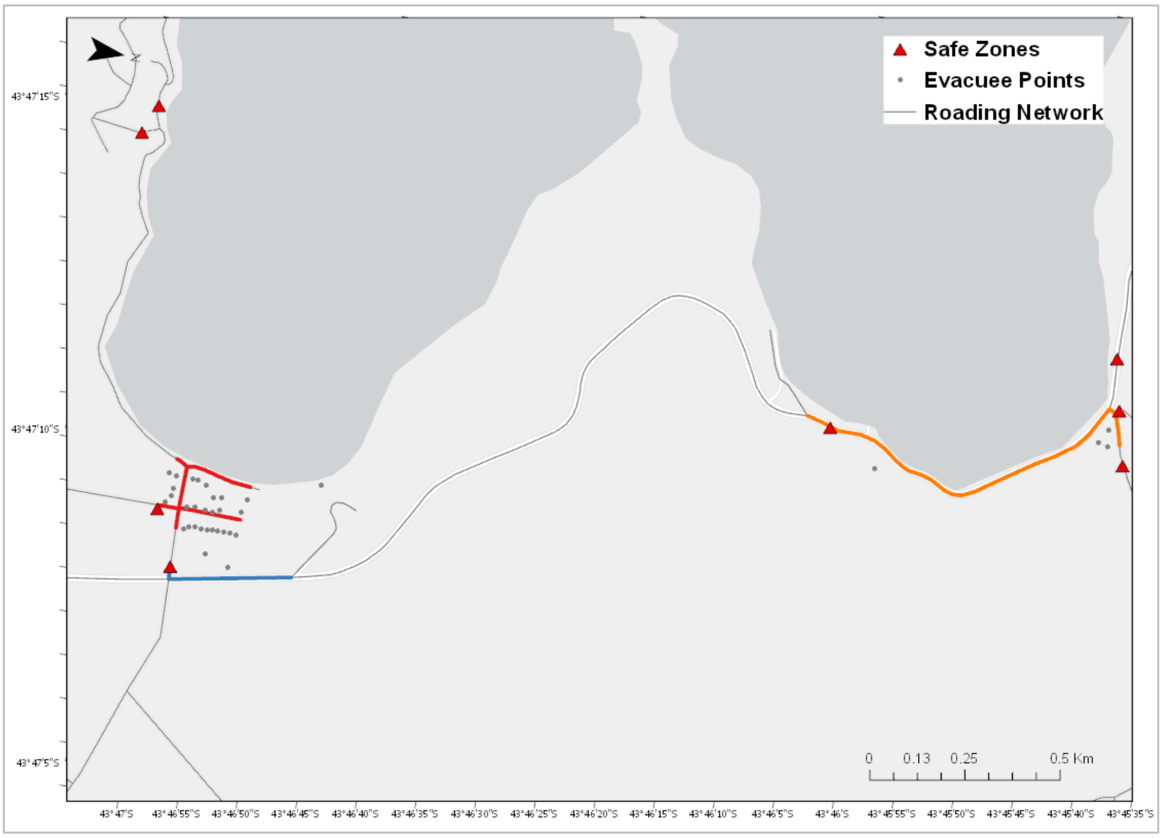

Figure 7.192: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

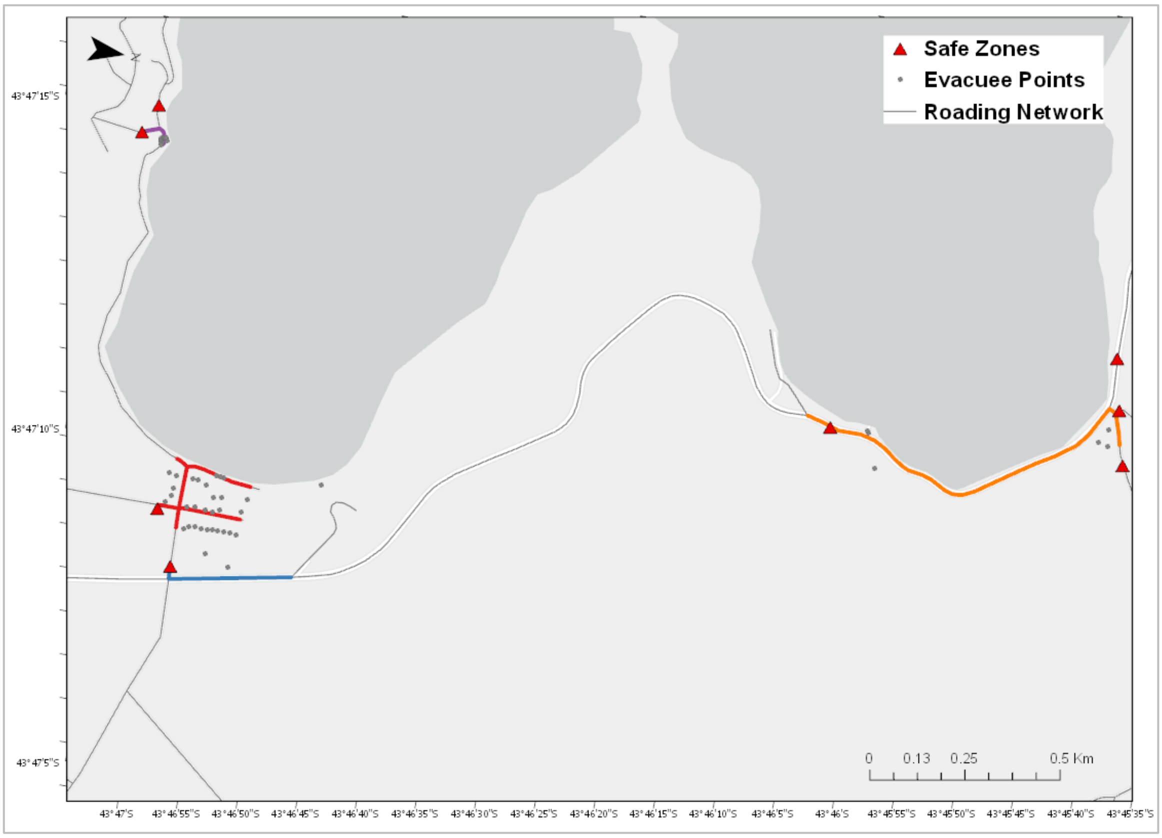

Figure 7.193: Safe zone distribution results for Takamatua Bay and Robinsons Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

i. Te Oka Bay, Tumbledown Bay and Magnet Bay

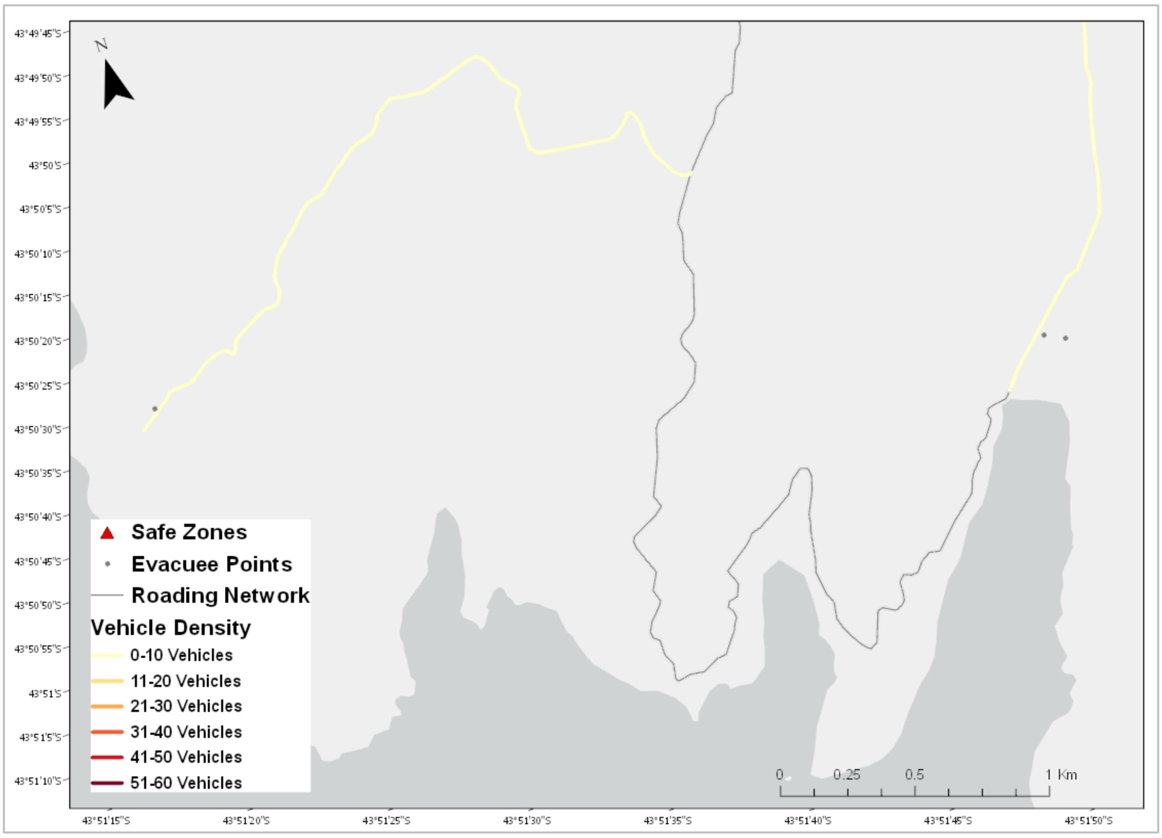

Figure 7.194: Vehicle density count results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

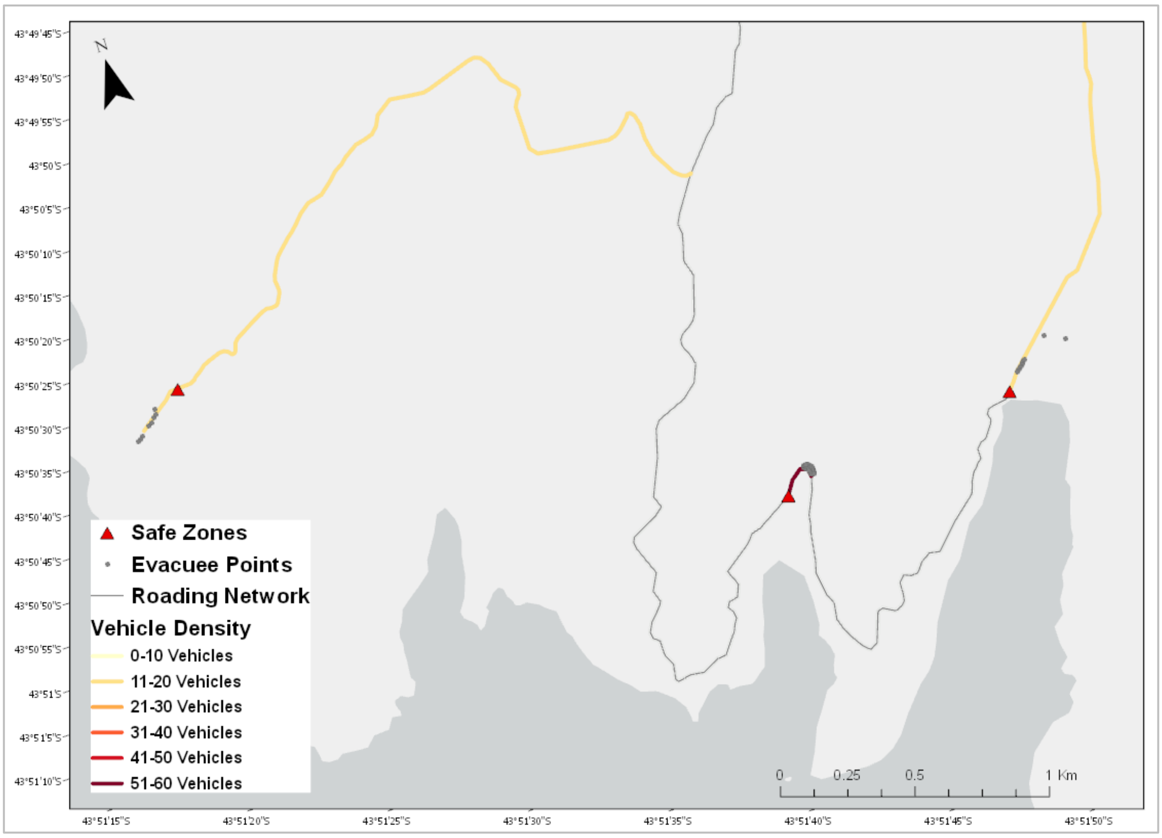

Figure 7.195: Vehicle density count results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

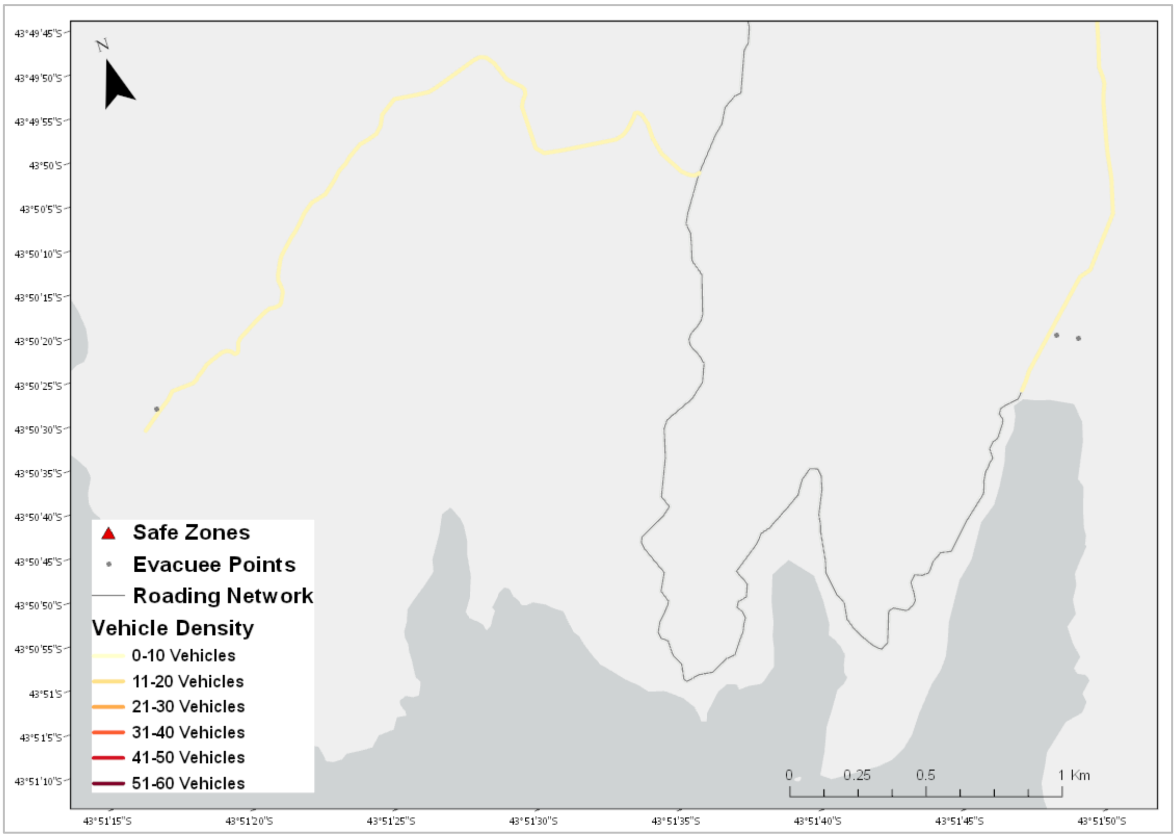

Figure 7.196: Vehicle density count results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

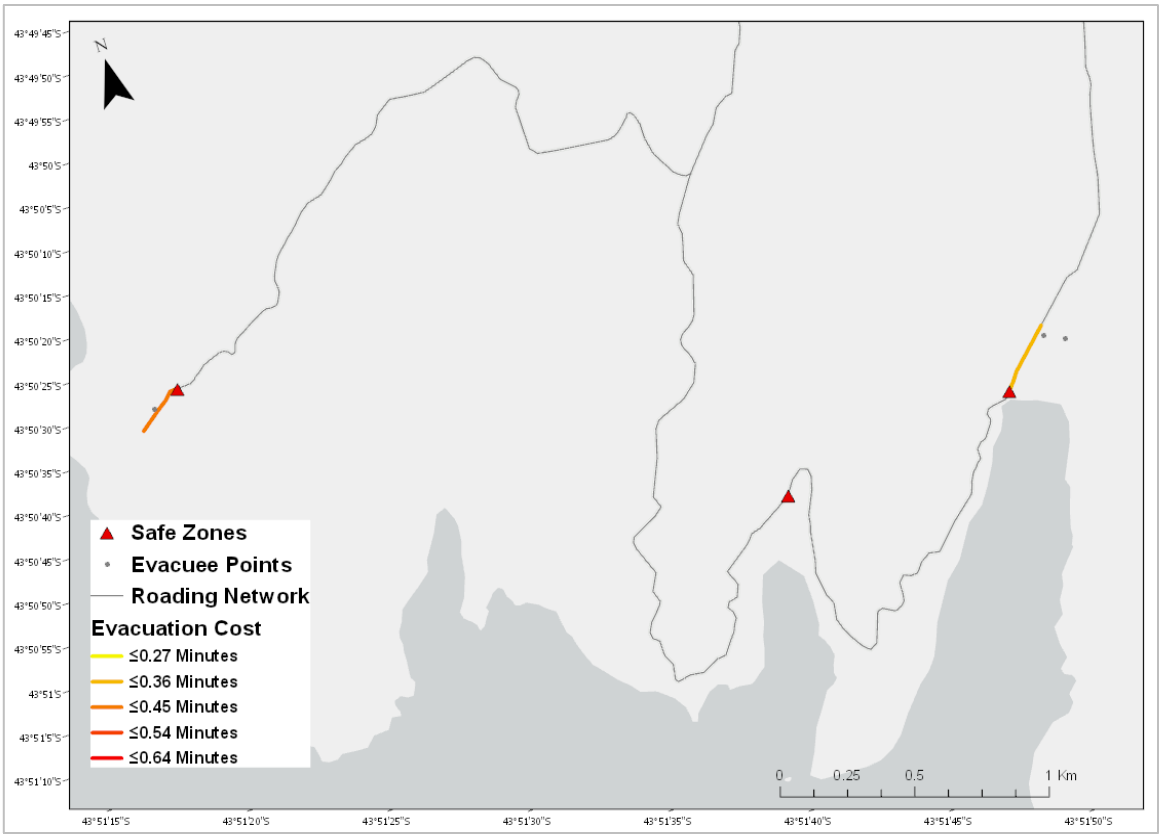

Figure 7.197: Evacuation cost results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

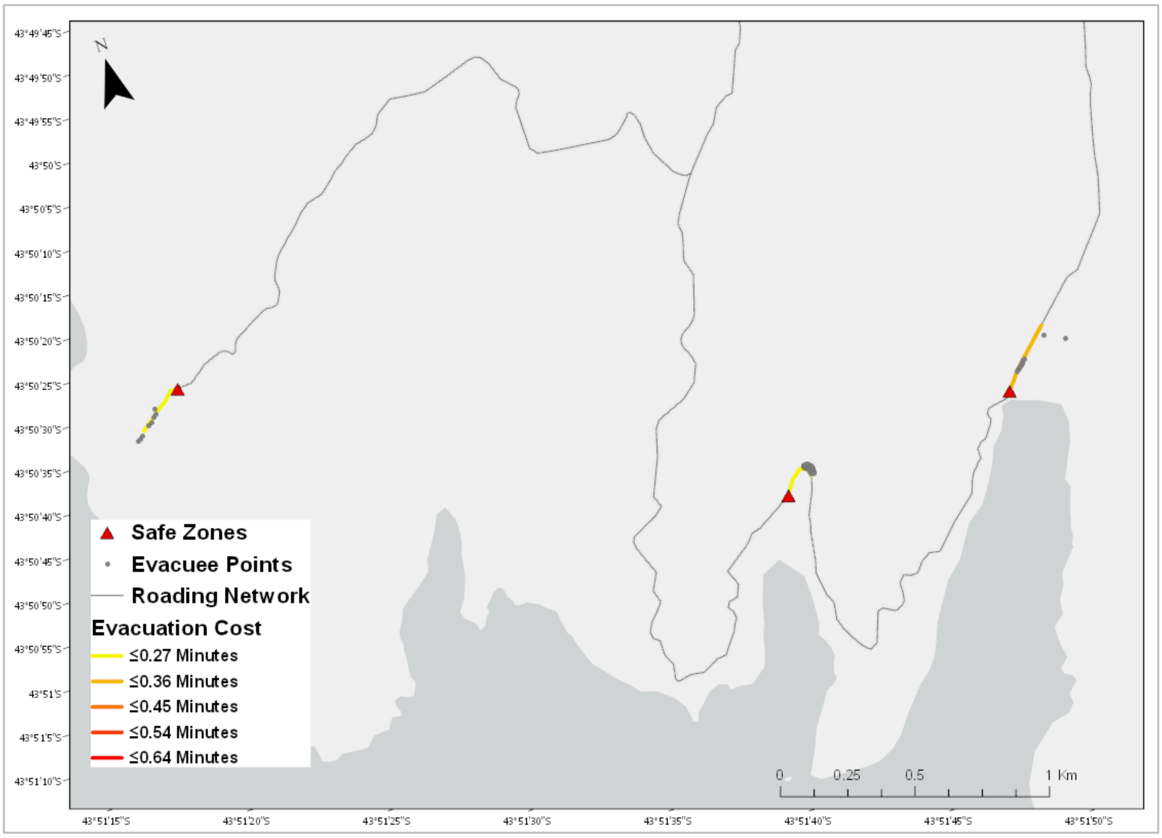

Figure 7.198: Evacuation cost results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

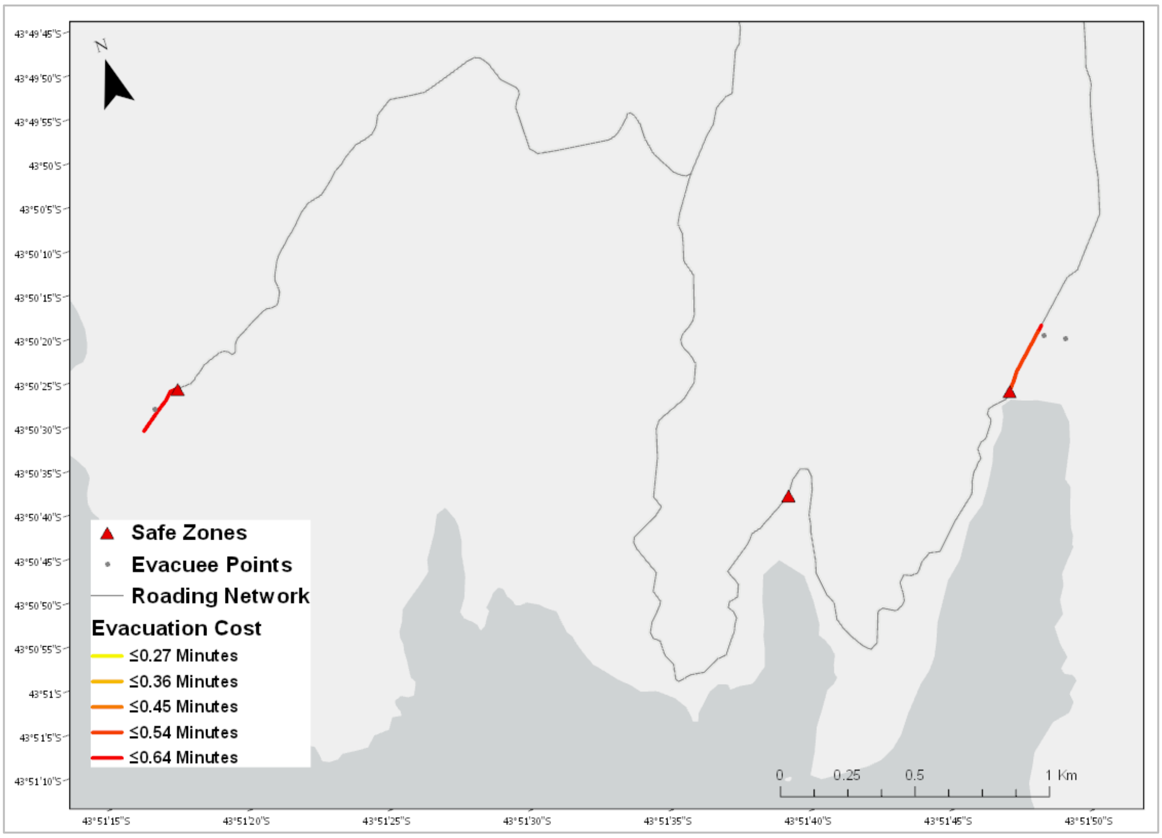

Figure 7.199: Evacuation cost results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

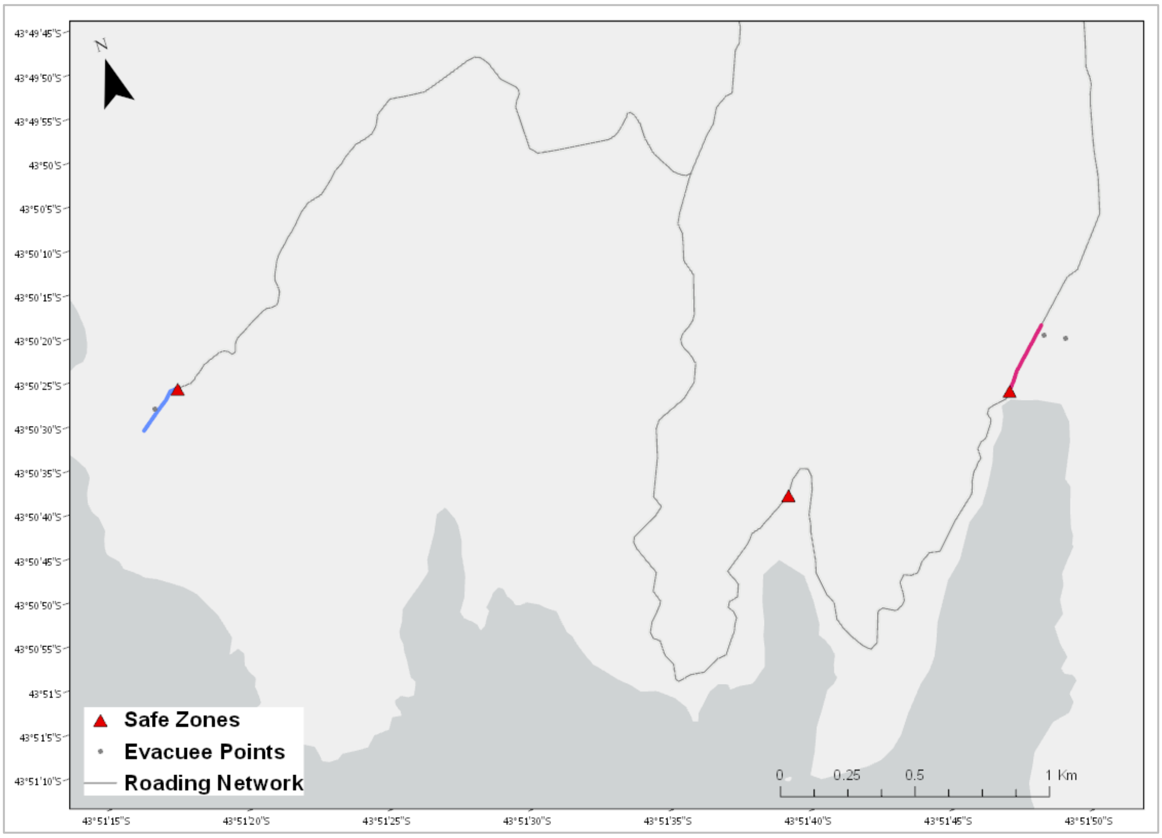

Figure 7.200: Safe zone distribution results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

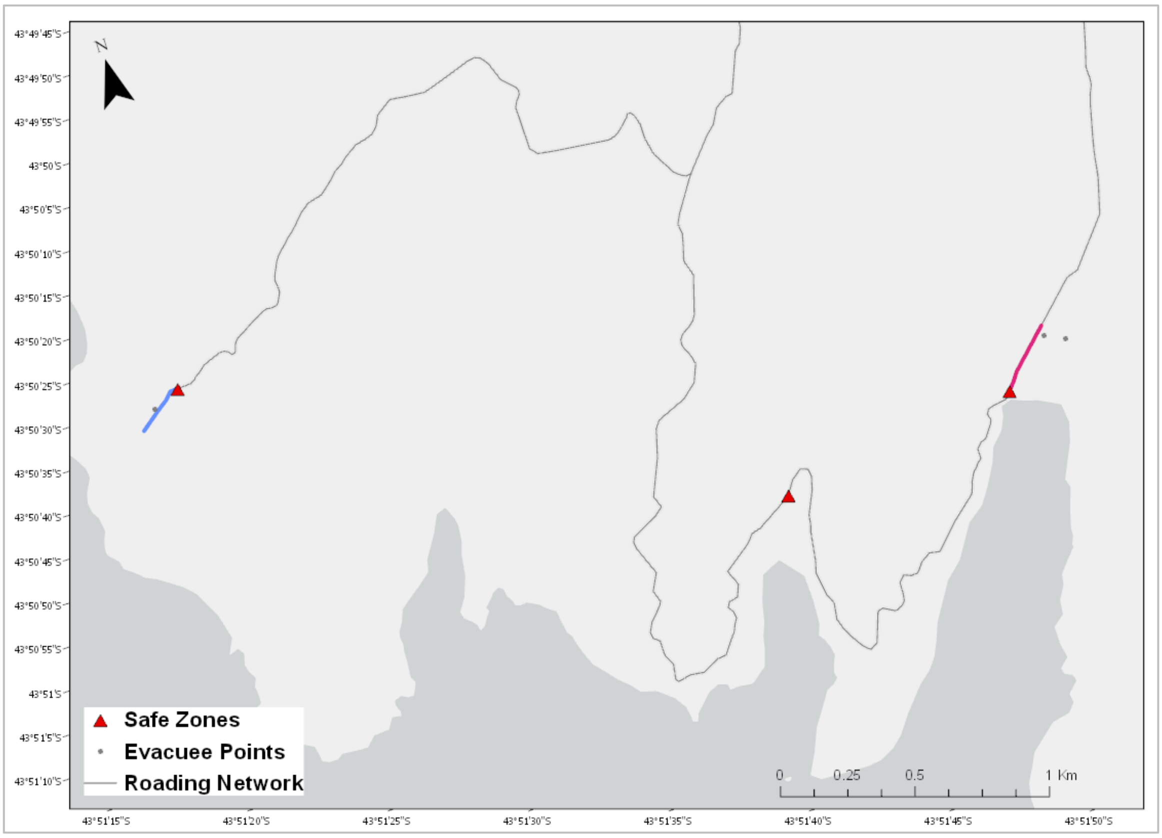

Figure 7.201: Safe zone distribution results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

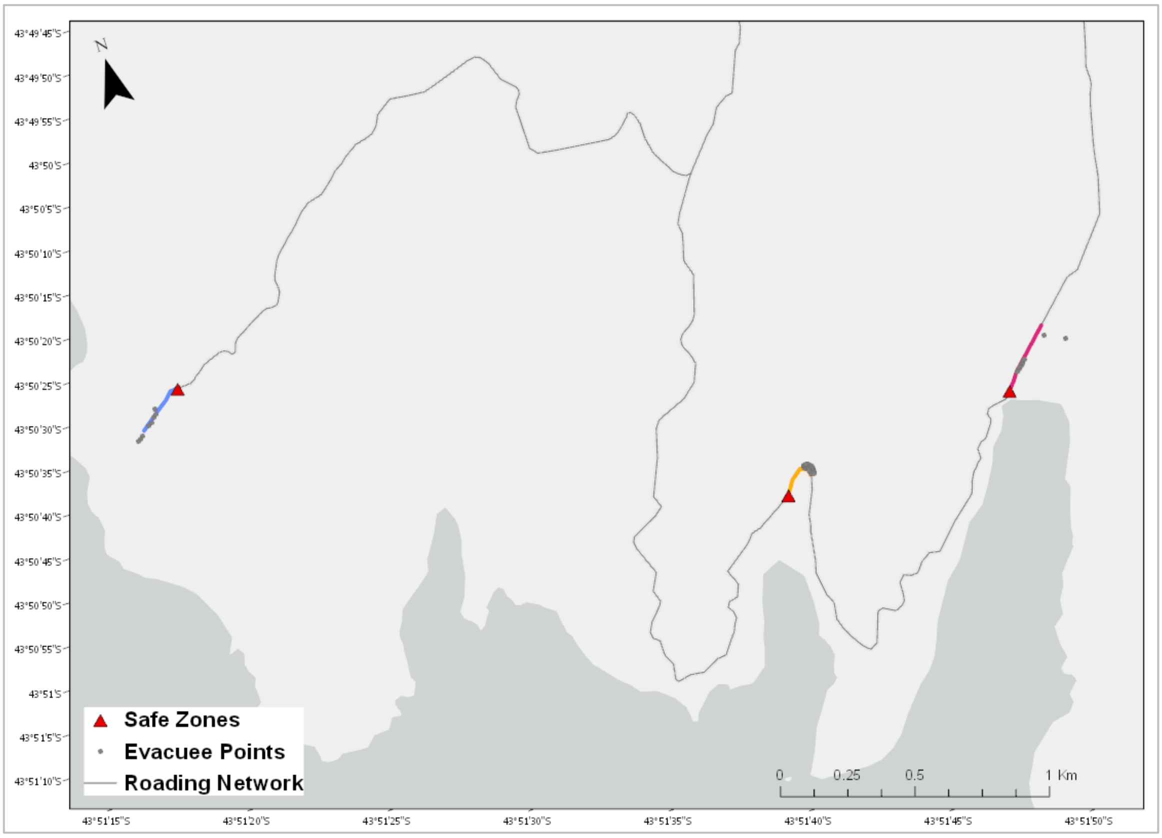

Figure 7.202: Safe zone distribution results for Te Oka Bay, Tumbledown Bay and Magnet Bay – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

j. Wainui

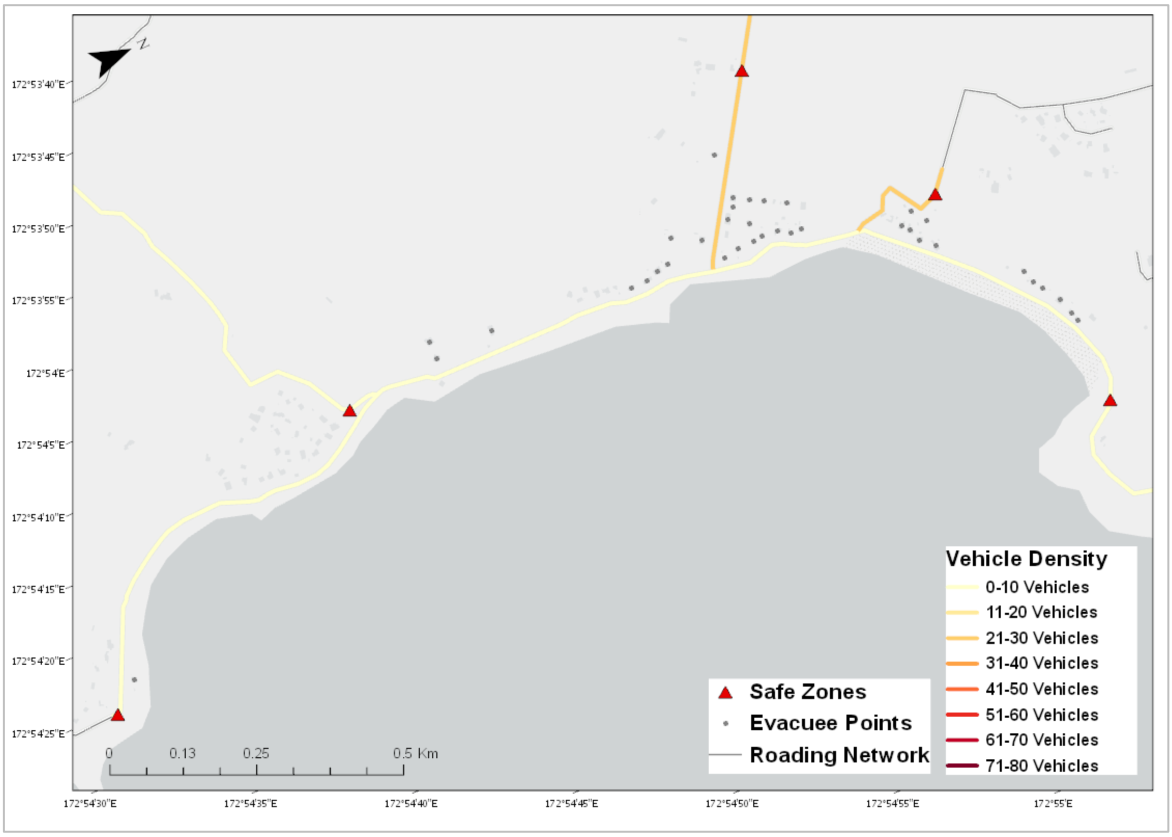

Figure 7.203: Vehicle density count results for Wainui – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

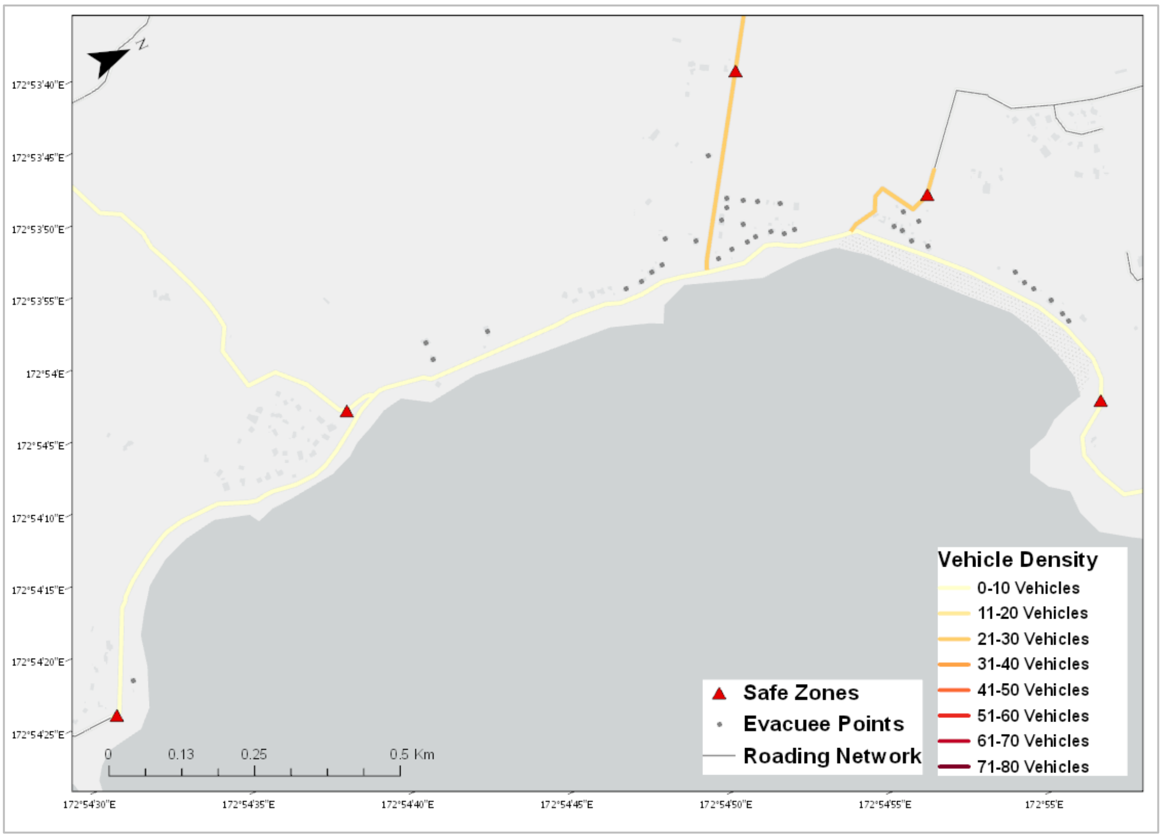

Figure 7.204: Vehicle density count results for Wainui – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

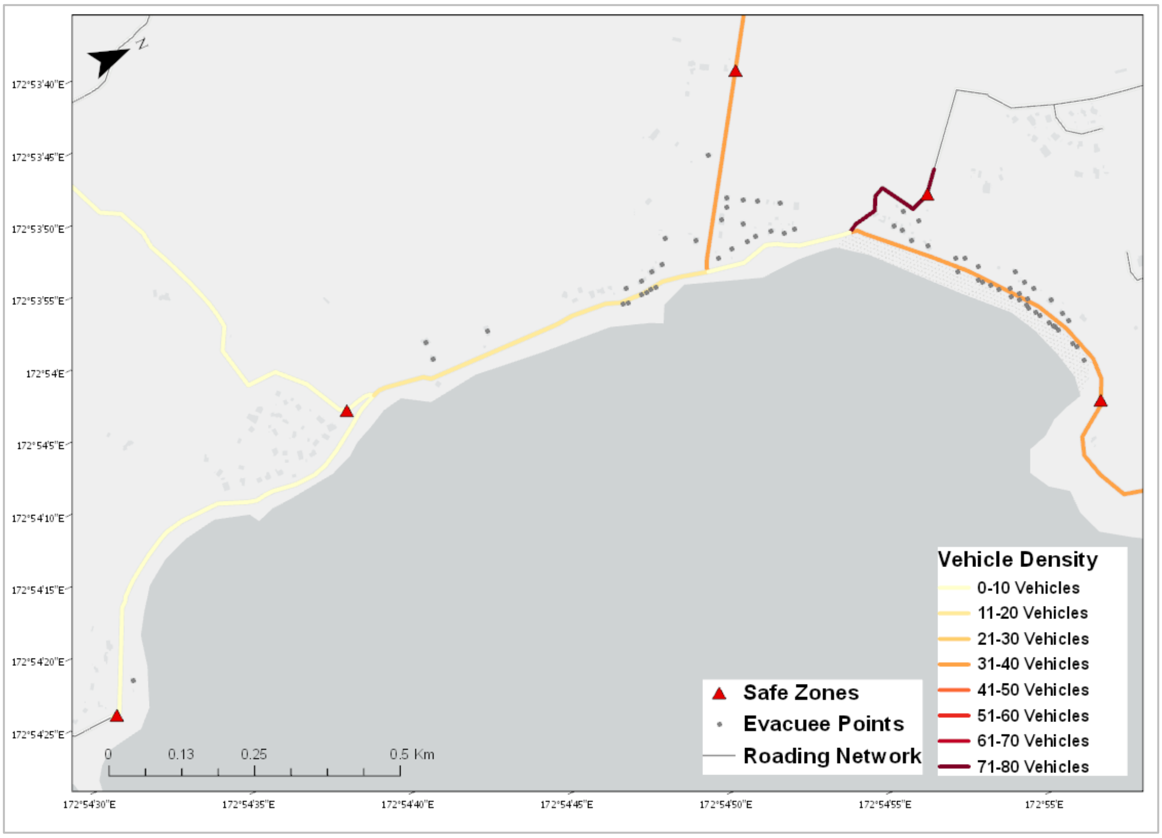

Figure 7.205: Vehicle density count results for Wainui – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

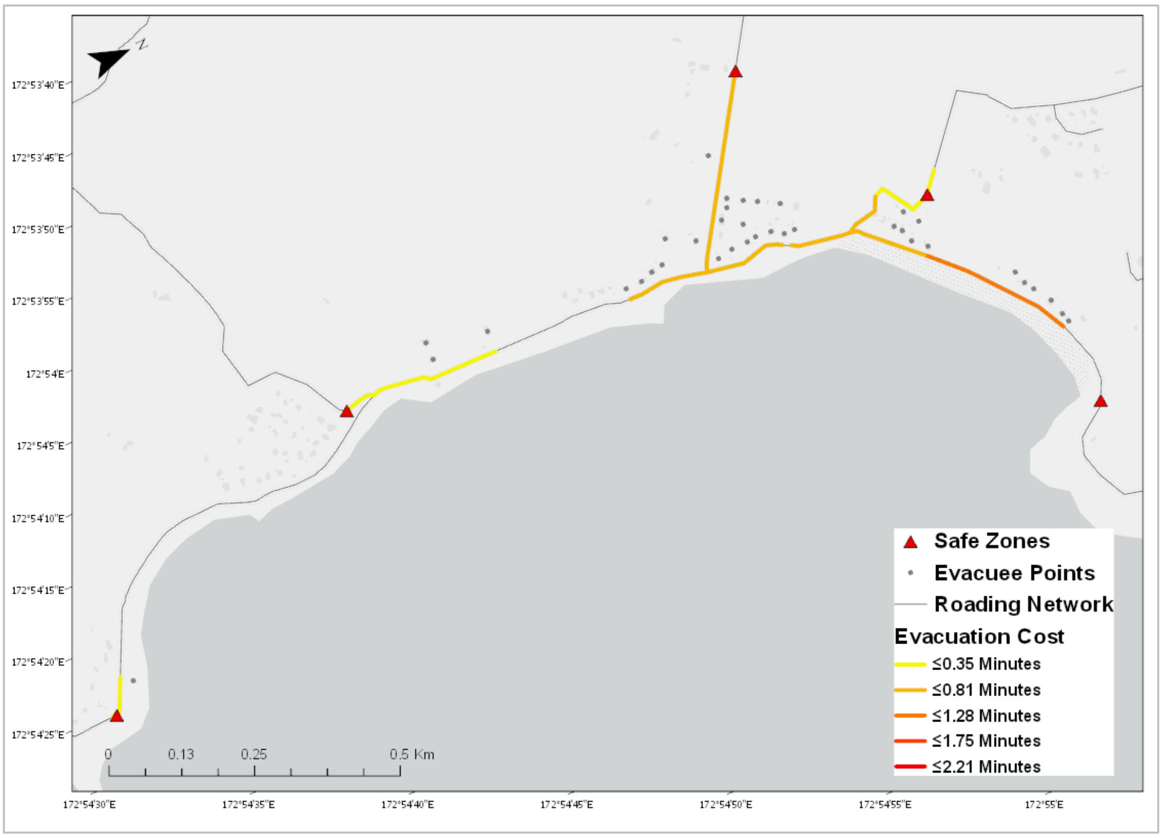

Figure 7.206: Evacuation cost results for Wainui – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

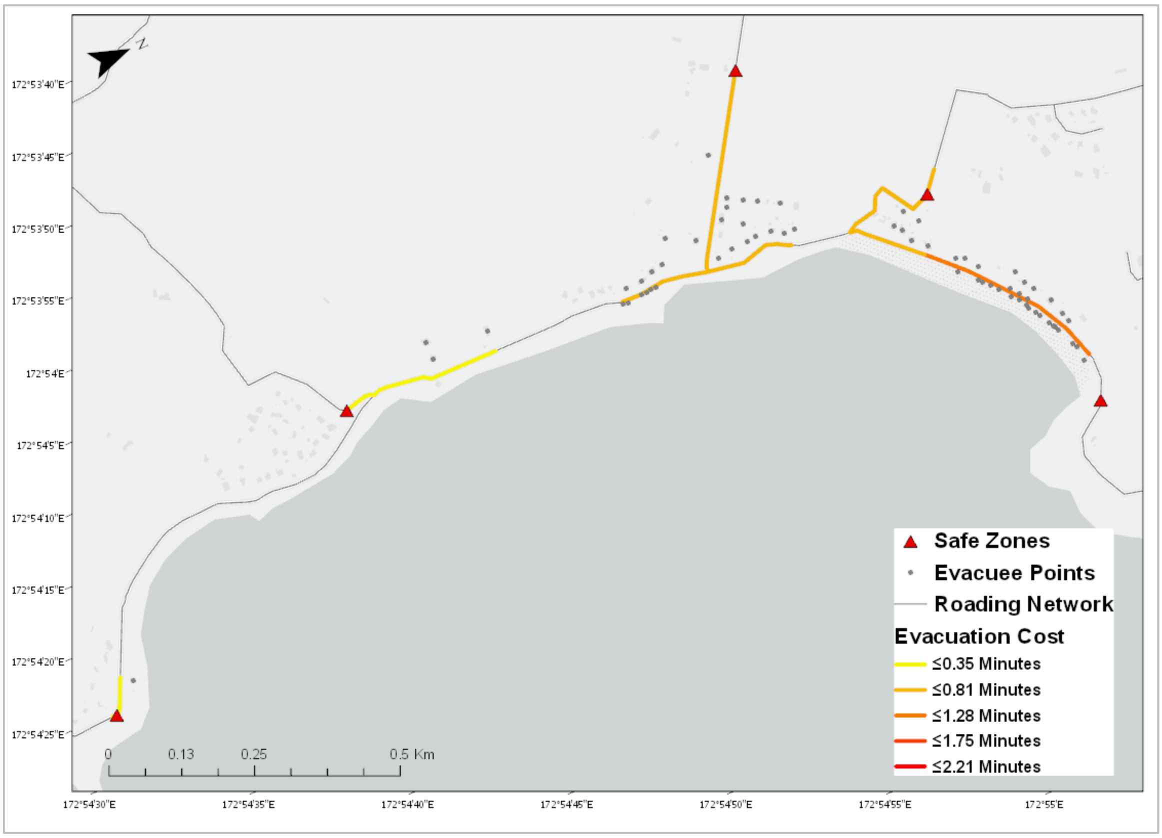

Figure 7.207: Evacuation cost results for Wainui – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

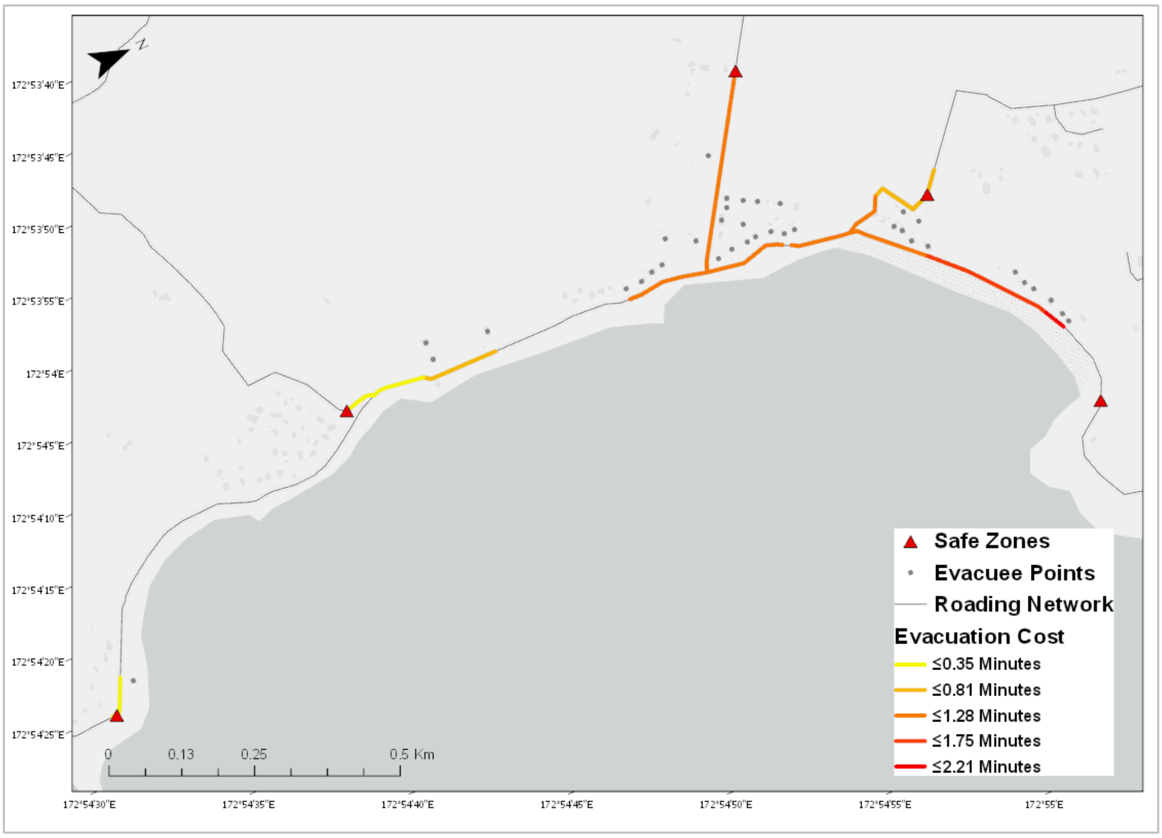

Figure 7.208: Evacuation cost results for Wainui – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

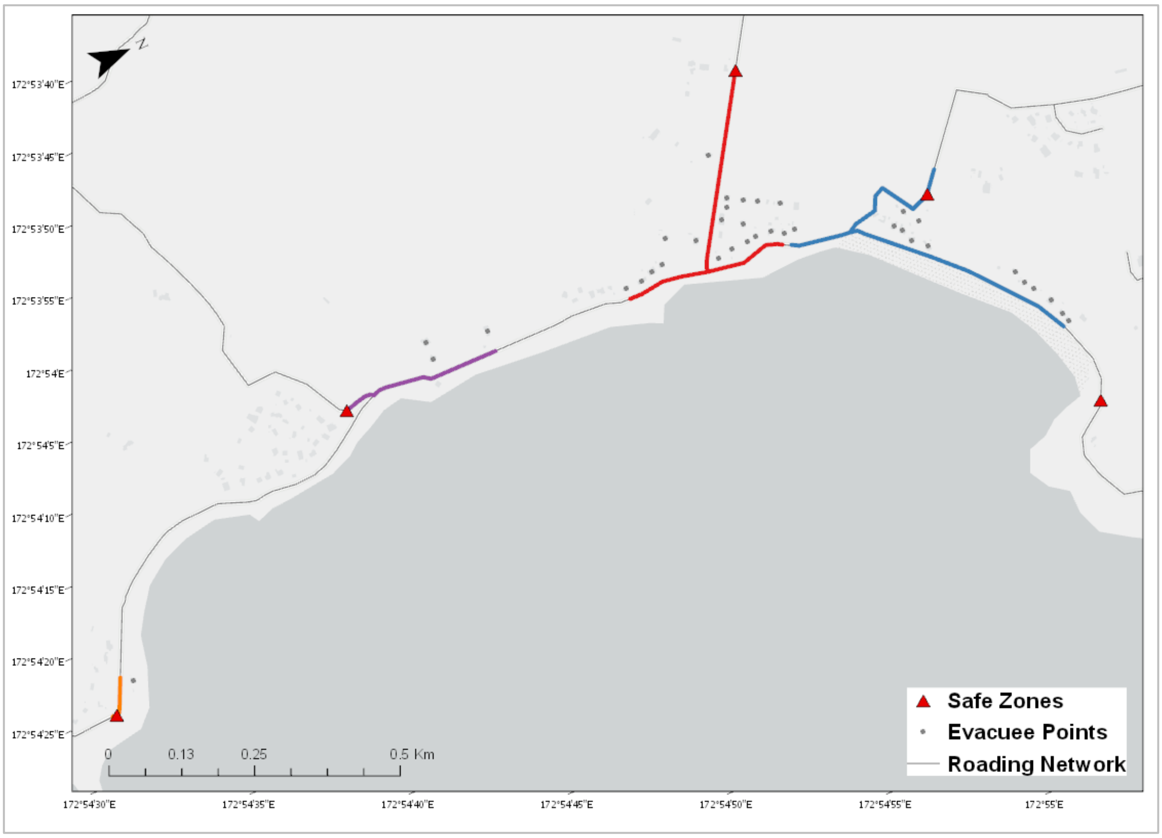

Figure 7.209: Safe zone distribution results for Wainui – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

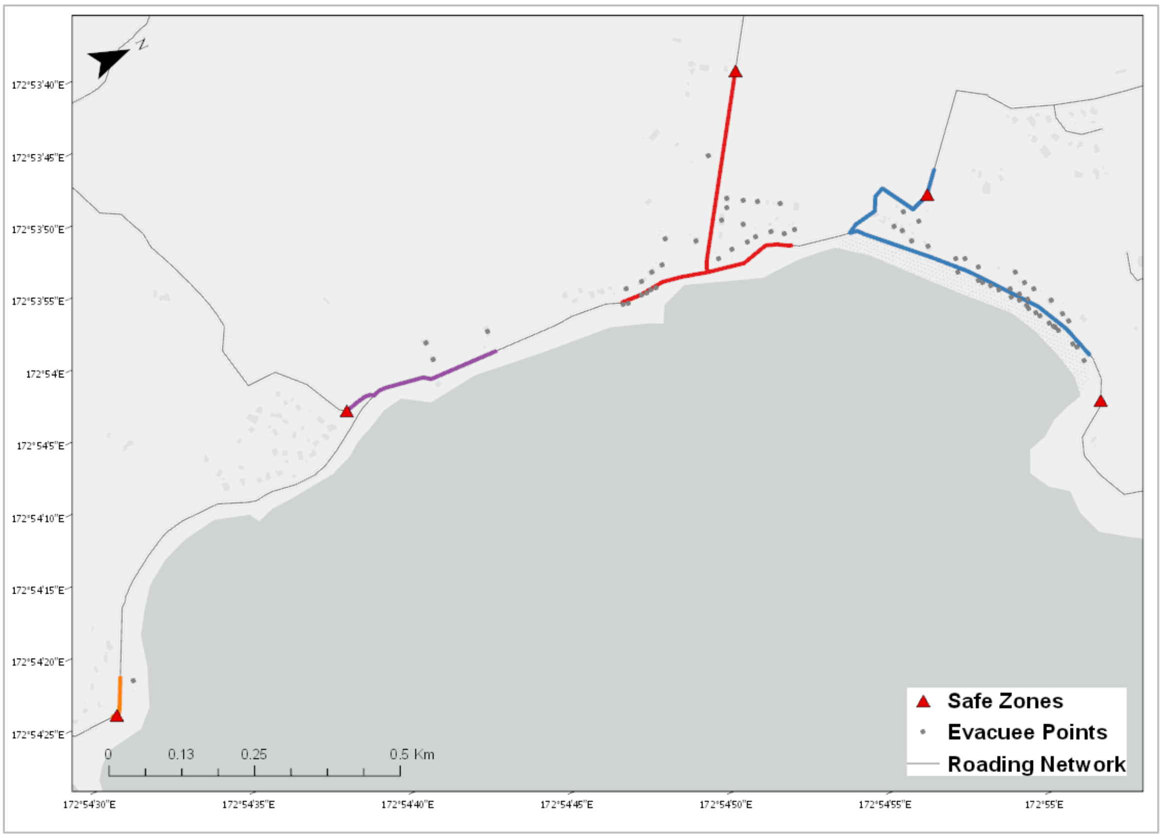

Figure 7.210: Safe zone distribution results for Wainui – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

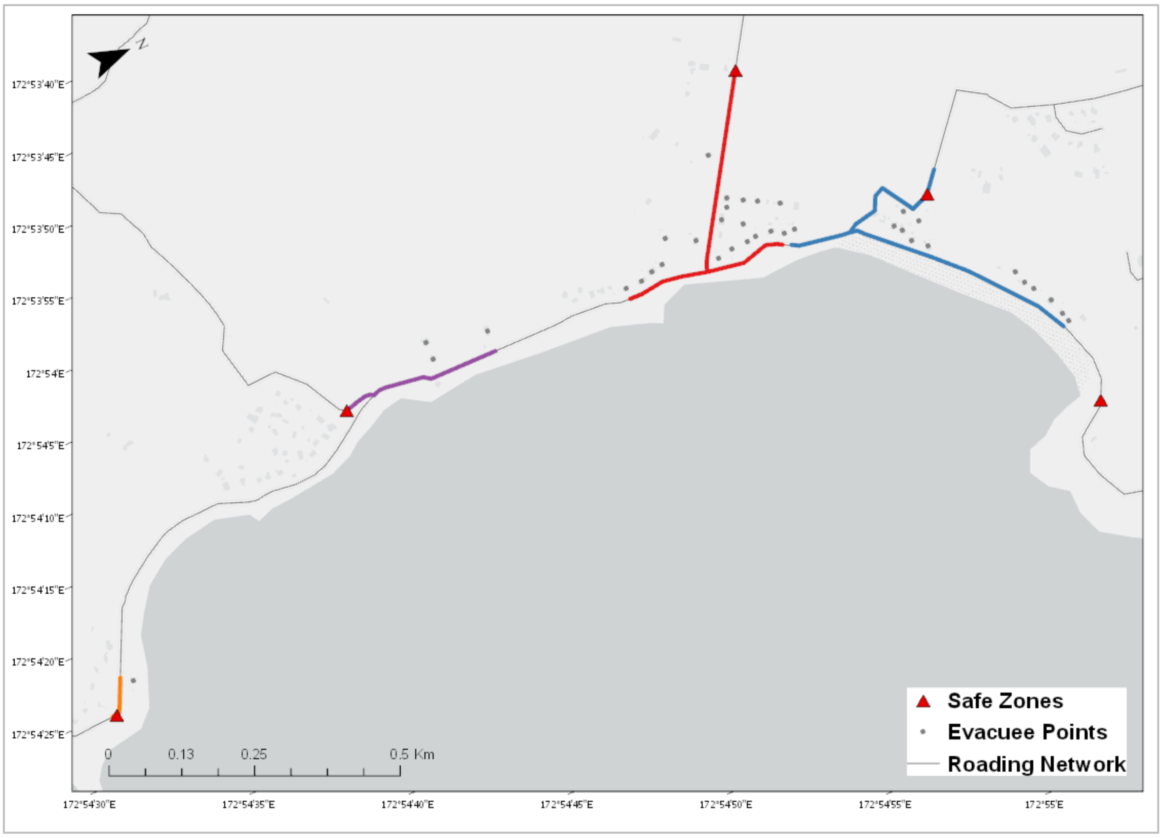

Figure 7.211: Safe zone distribution results for Wainui – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

vi. Reduced Safe Zones

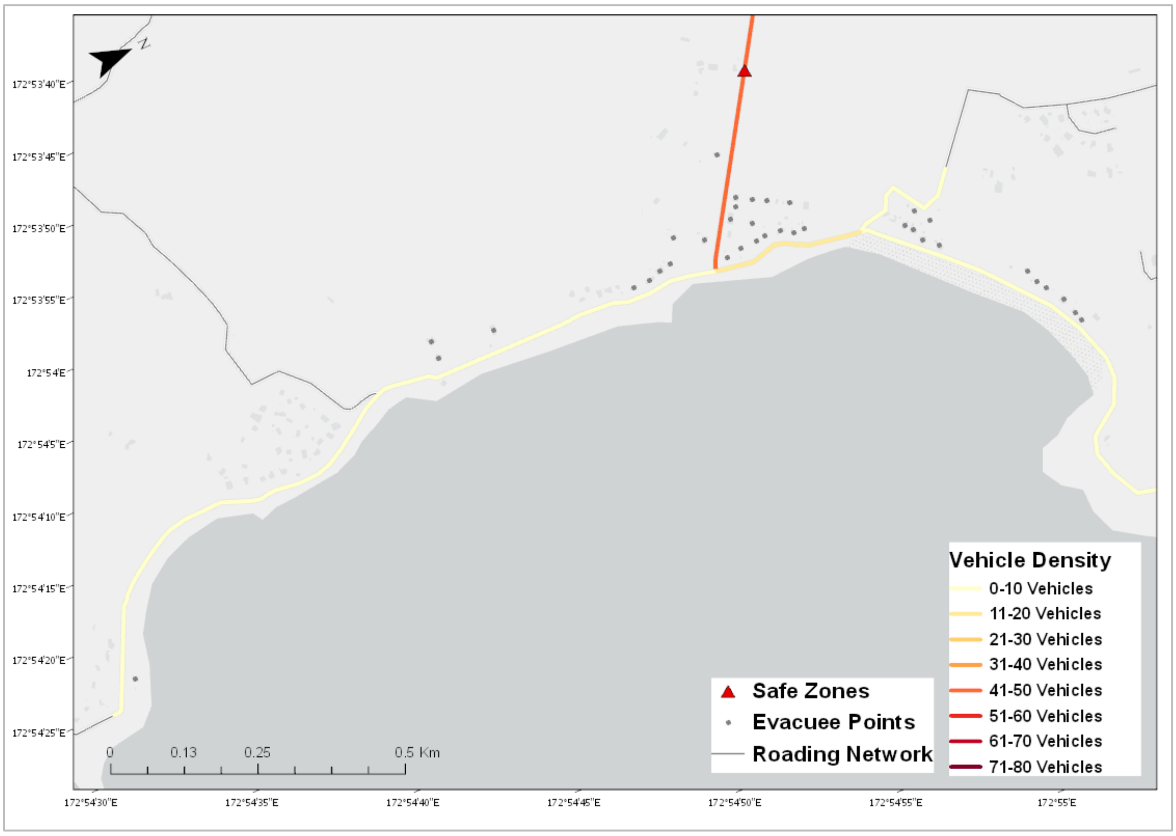

Figure 7.212: Vehicle density count results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

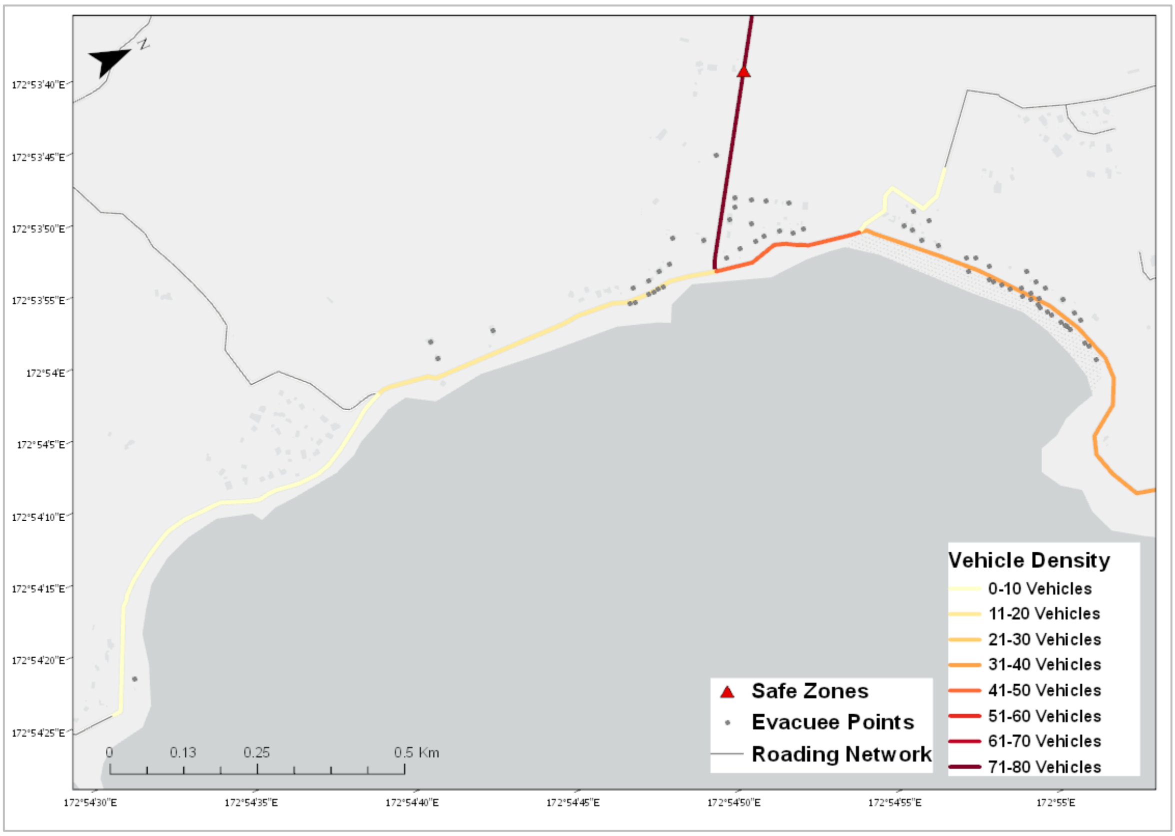

Figure 7.213: Vehicle density count results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

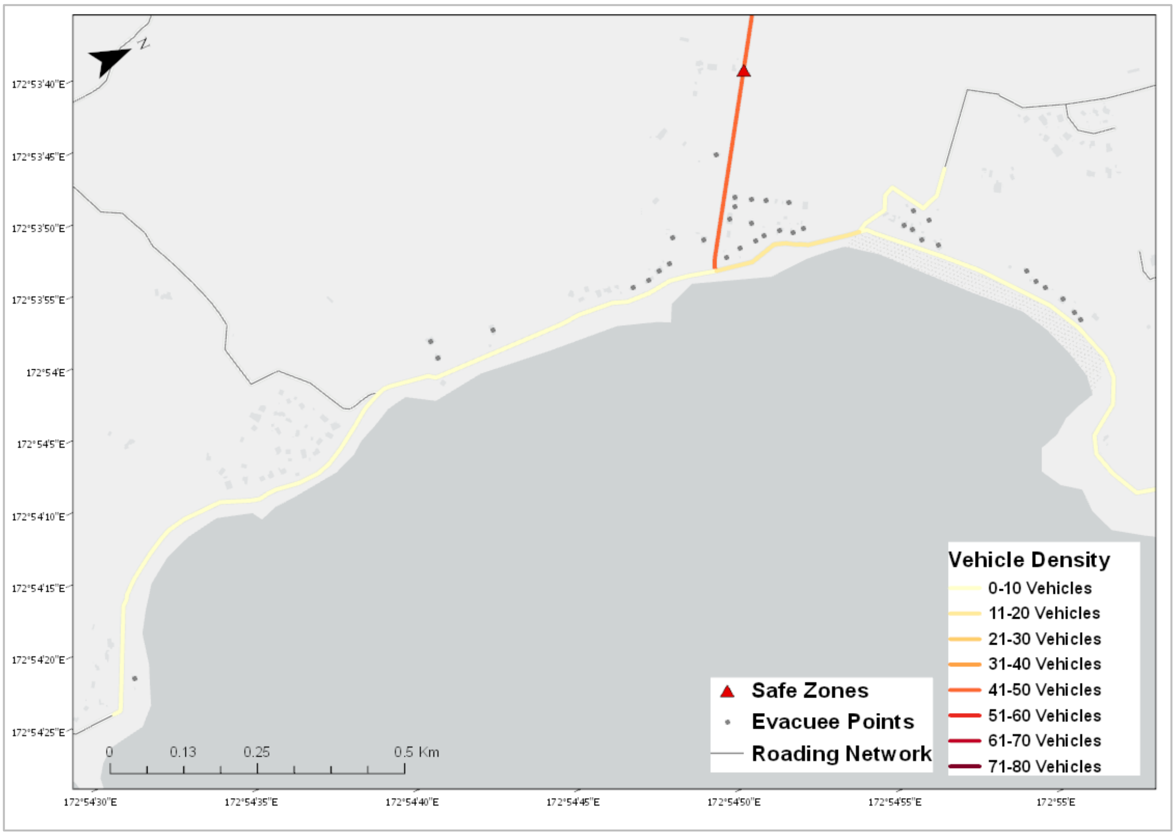

Figure 7.214: Vehicle density count results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

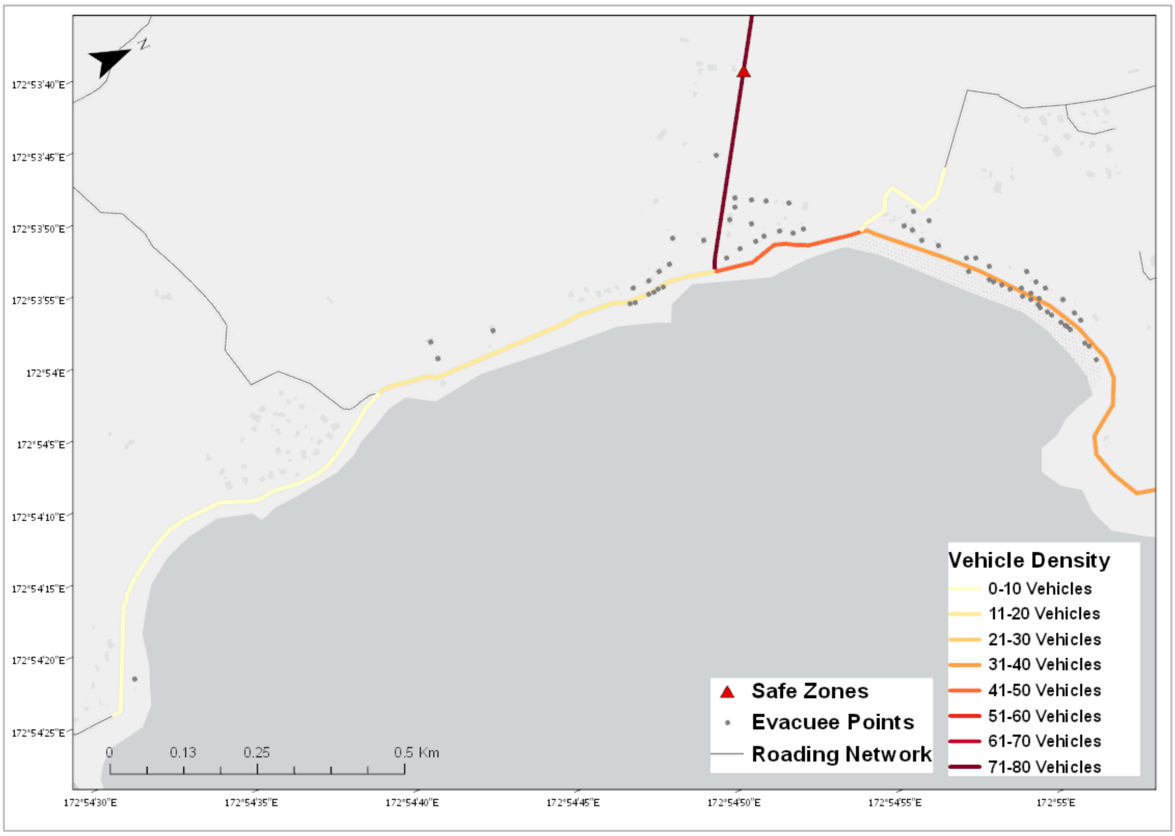

Figure 7.215: Vehicle density count results for Okains Bay when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

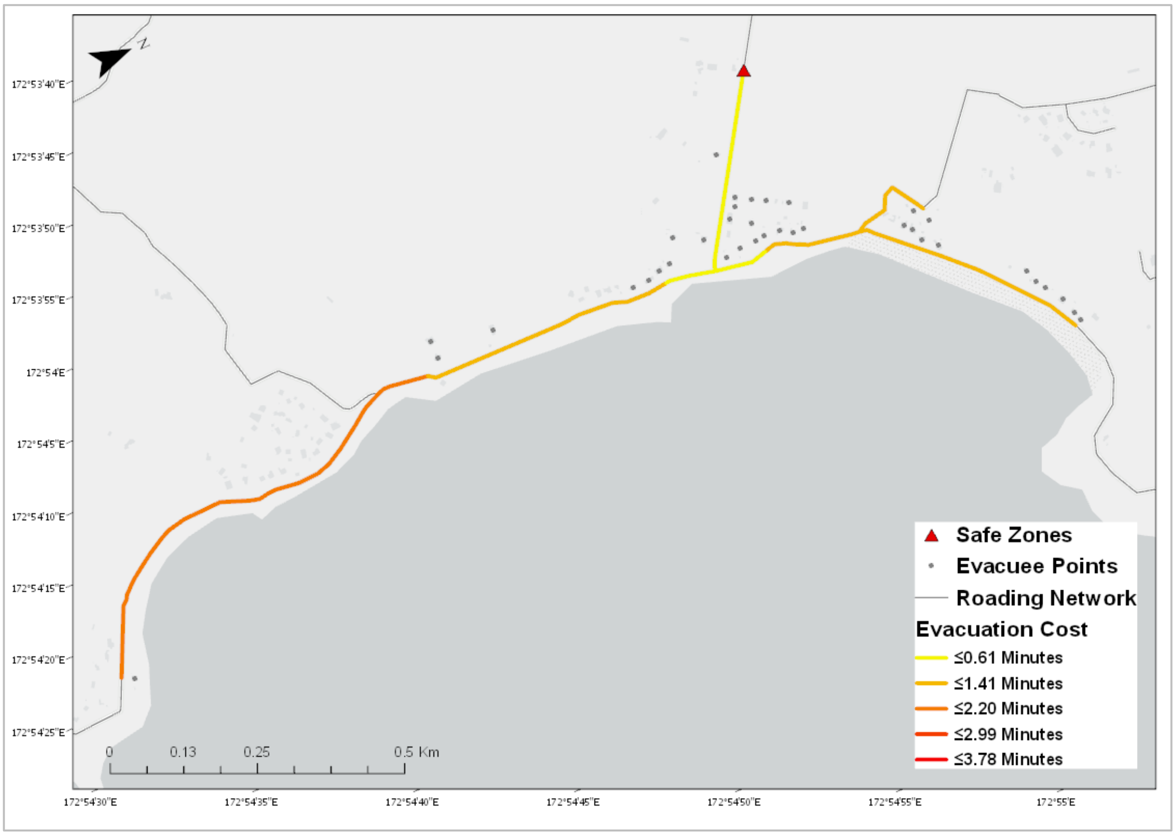

Figure 7.216: Evacuation cost results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

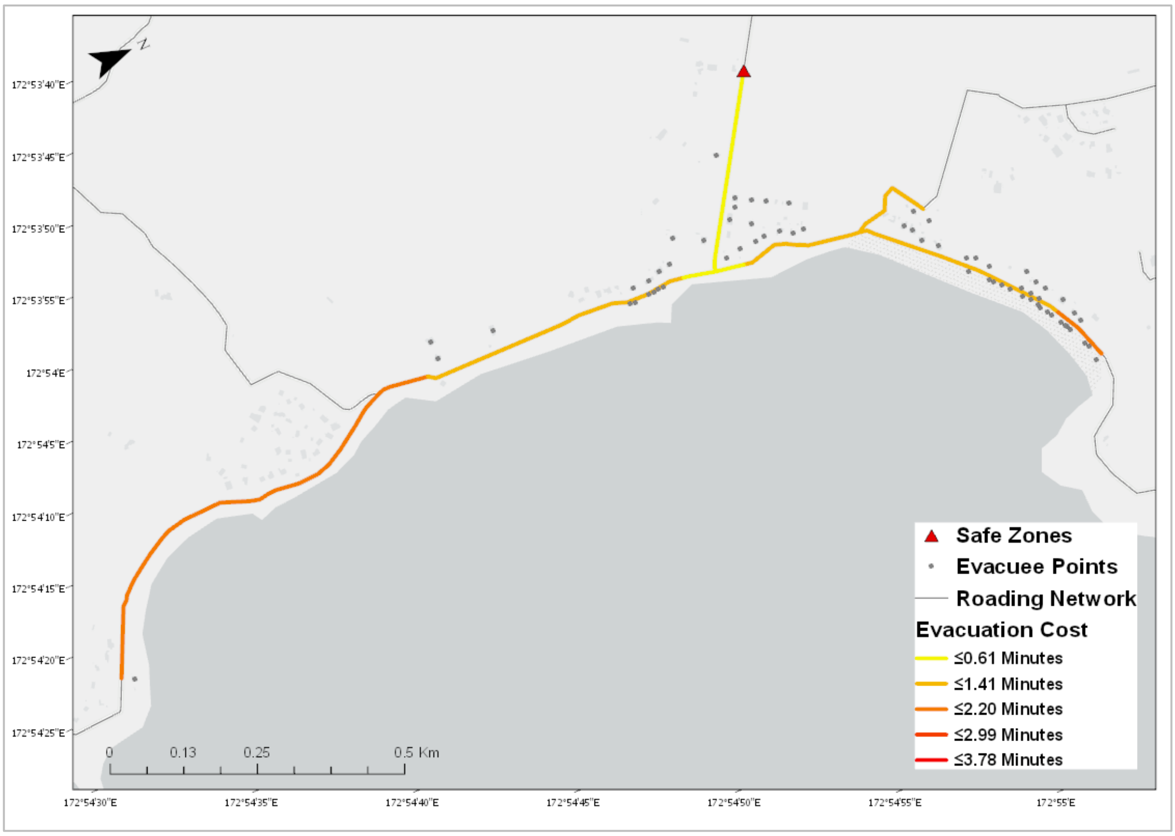

Figure 7.217: Evacuation cost results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

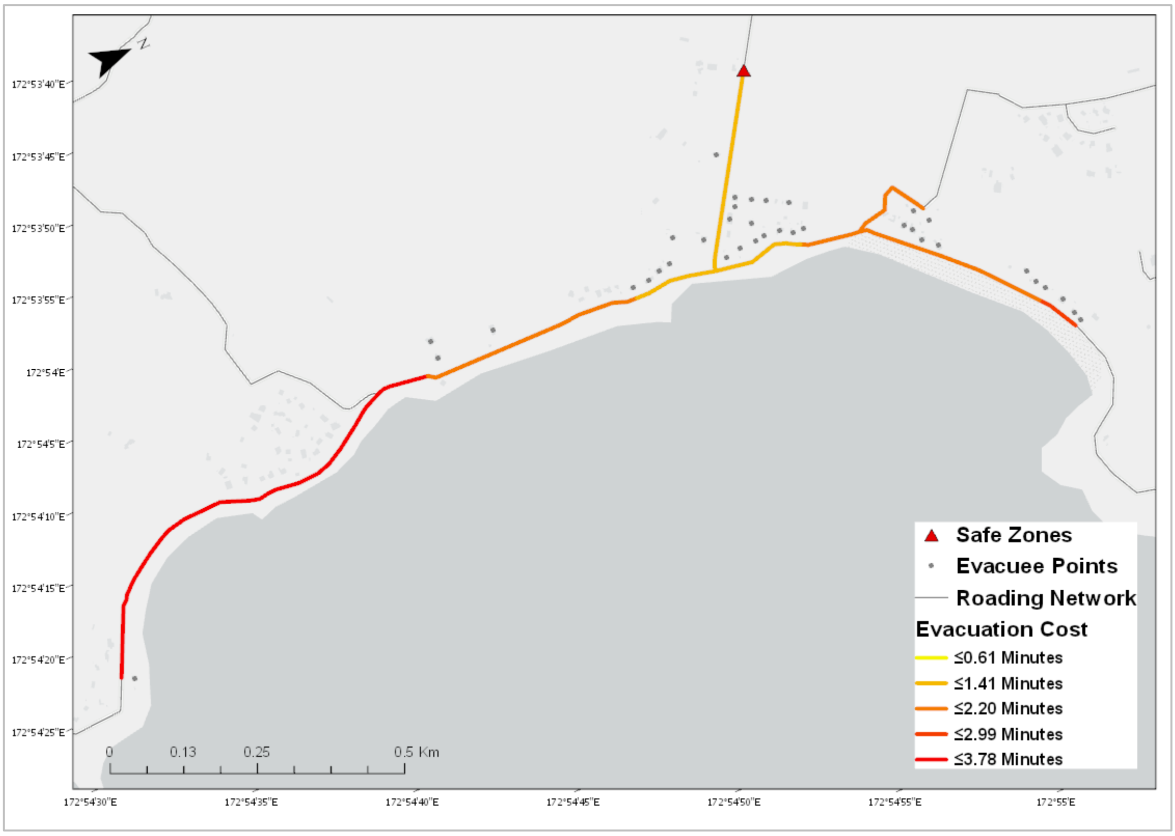

Figure 7.218: Evacuation cost results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

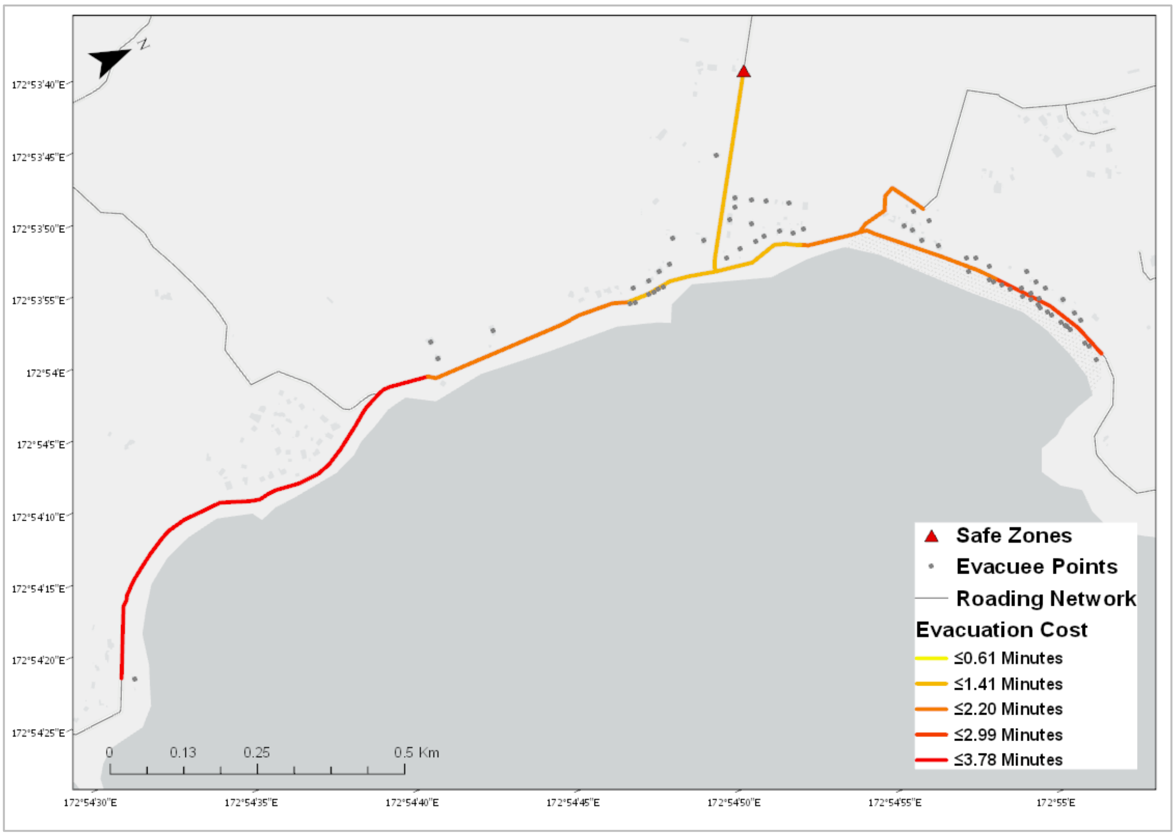

Figure 7.219: Evacuation cost results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

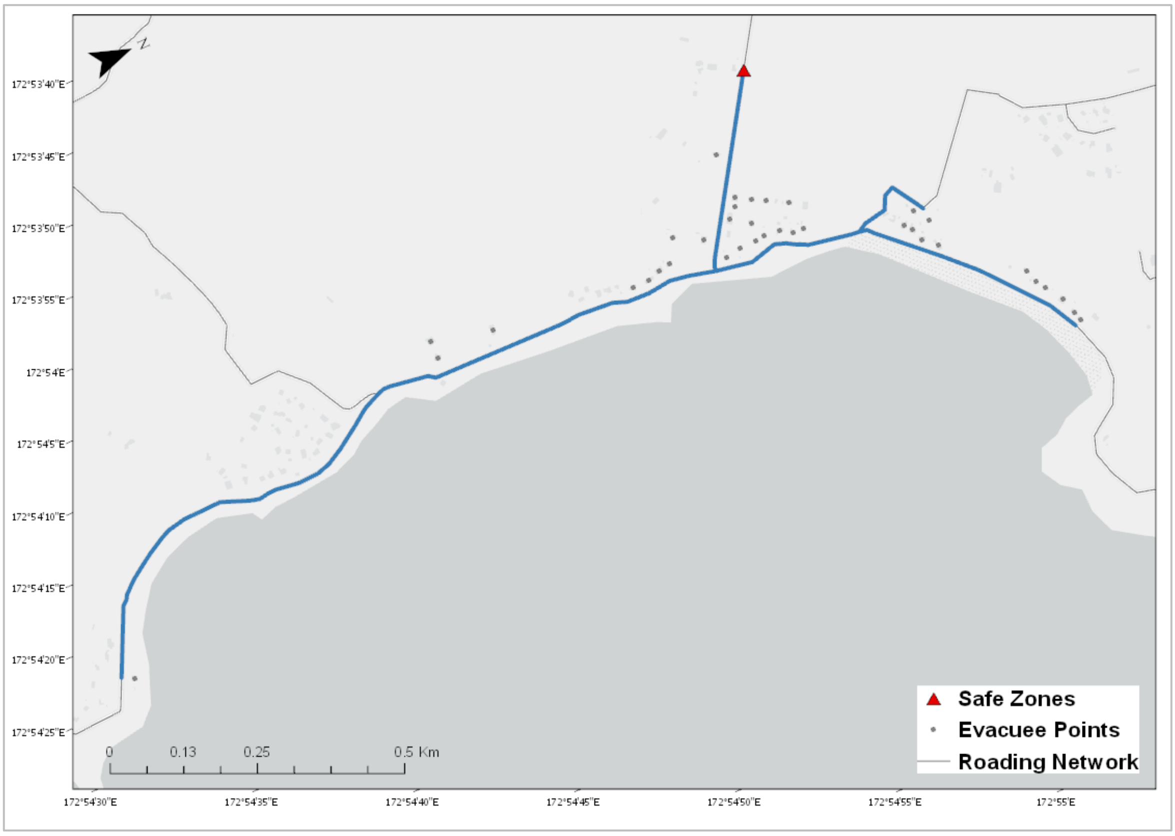

Figure 7.220: Safe zone distribution results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a normal traffic scenario.

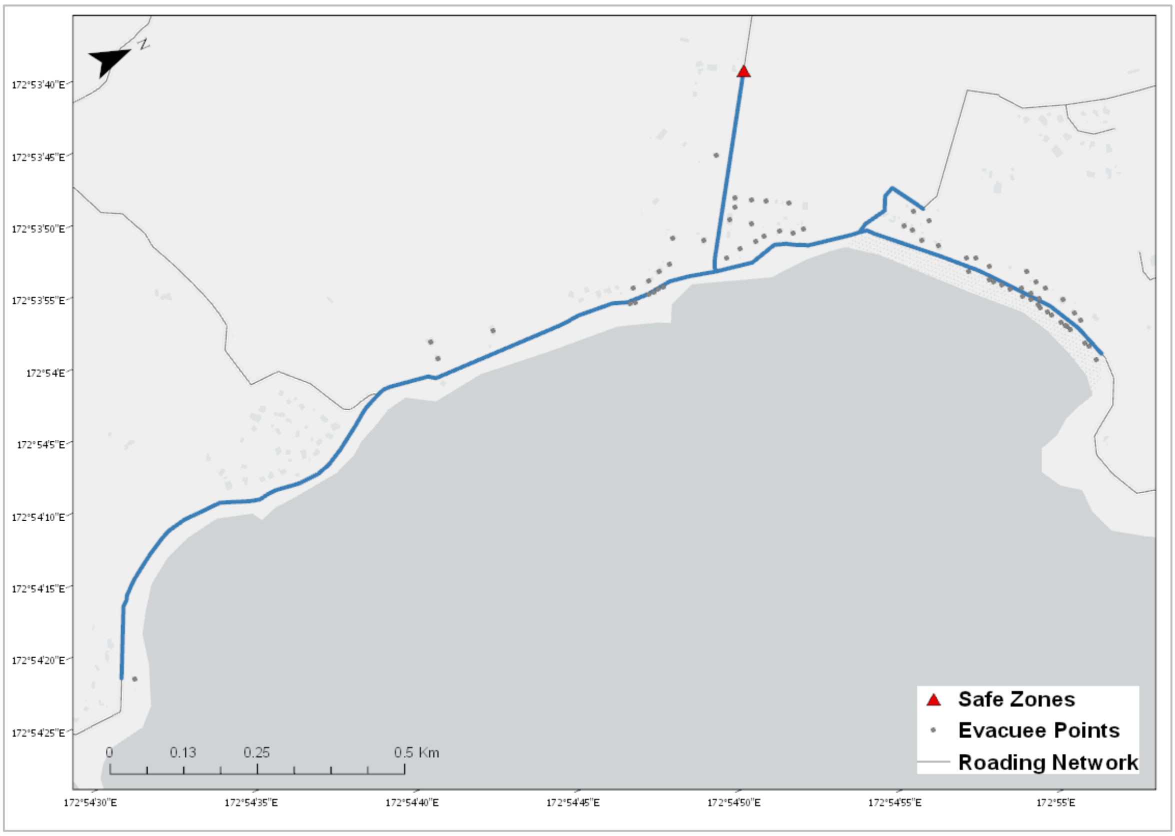

Figure 7.221: Safe zone distribution results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 50 km/hr during a peak day traffic scenario.

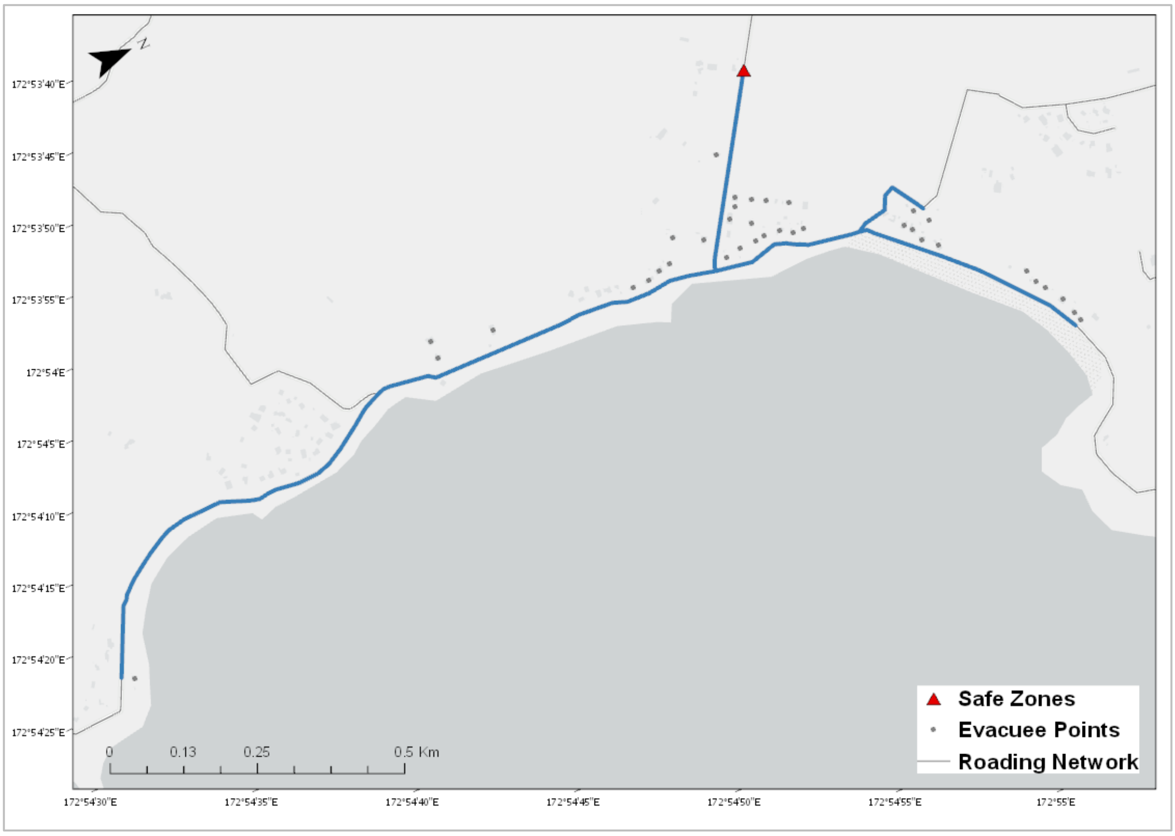

Figure 7.222: Safe zone distribution results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a normal traffic scenario.

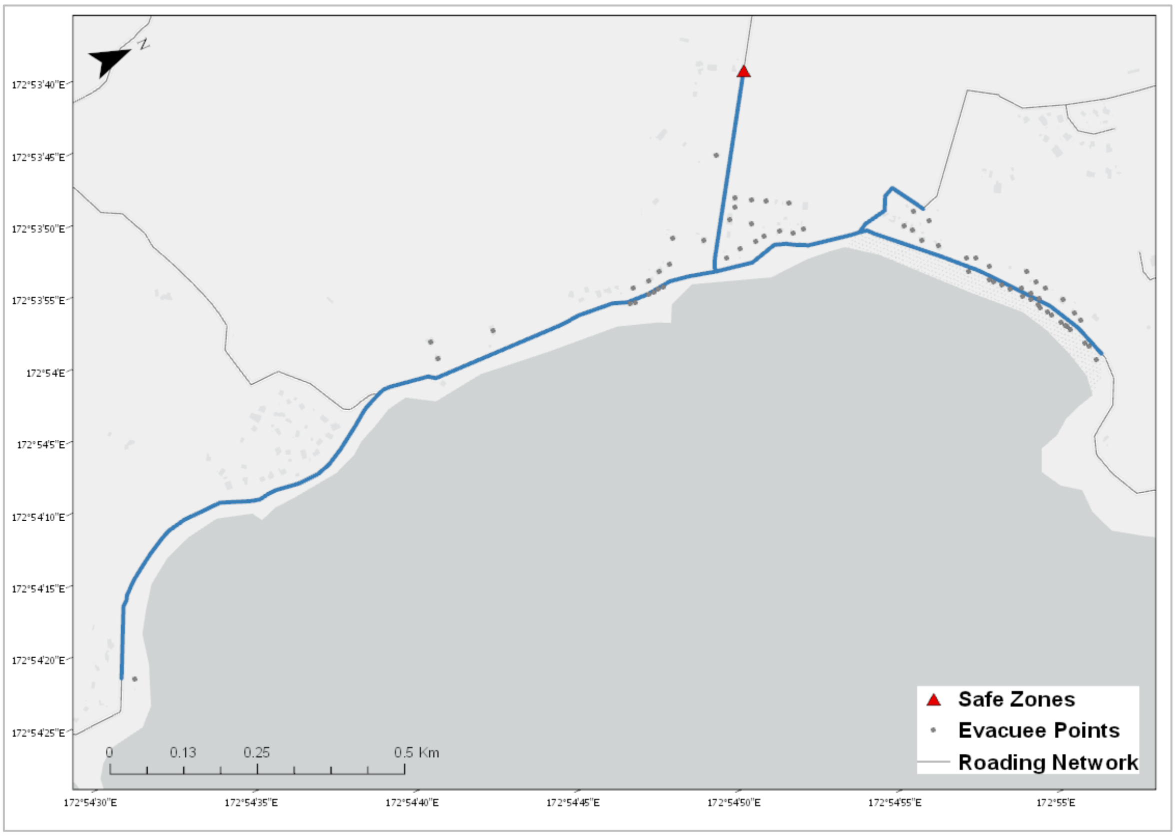

Figure 7.223: Safe zone distribution results for Wainui when the number of safe zones have been reduced – modelled at an evacuation speed of 28.1 km/hr during a peak day traffic scenario.

k. Evacuation Modelling Origin Point Issues

This section provides spatial details on the evacuee origin points that were not initially included by the CASPER evacuation modelling tool and had to be relocated to be included within the modelling results.

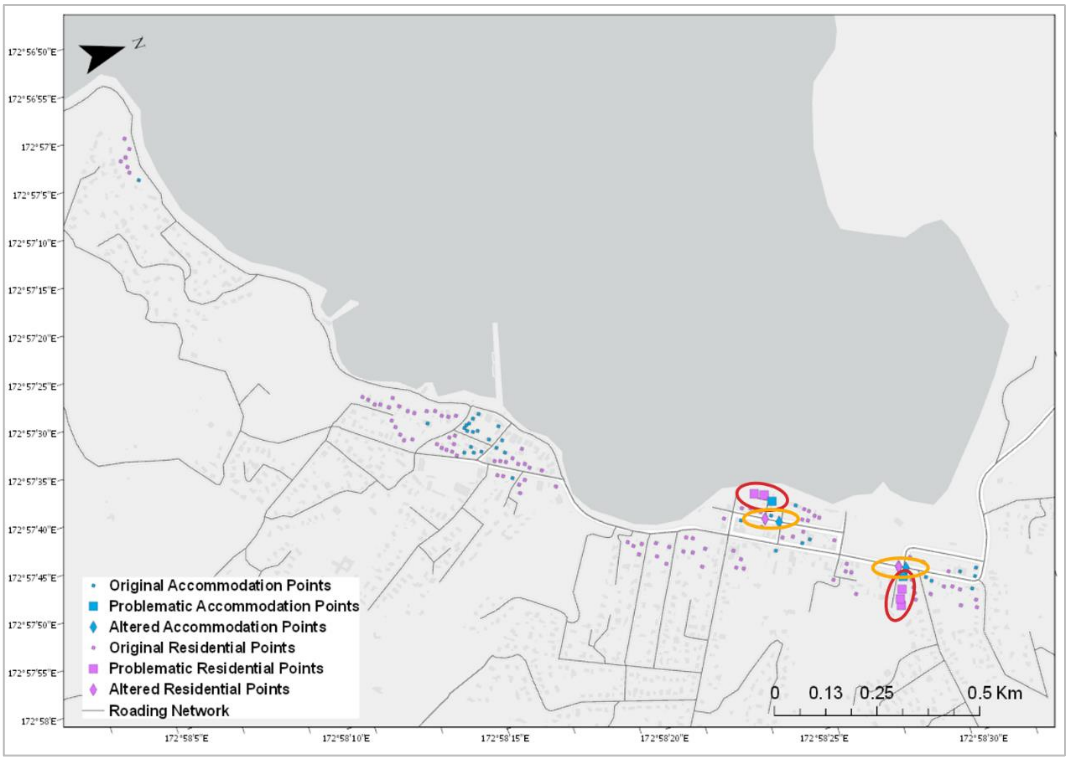

Figure 7.224: Original locations of input residential and accommodation points for Akaroa. Squares represent points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circles). The diamonds represent where the points were moved to ensure the model worked successfully (in the orange circles).

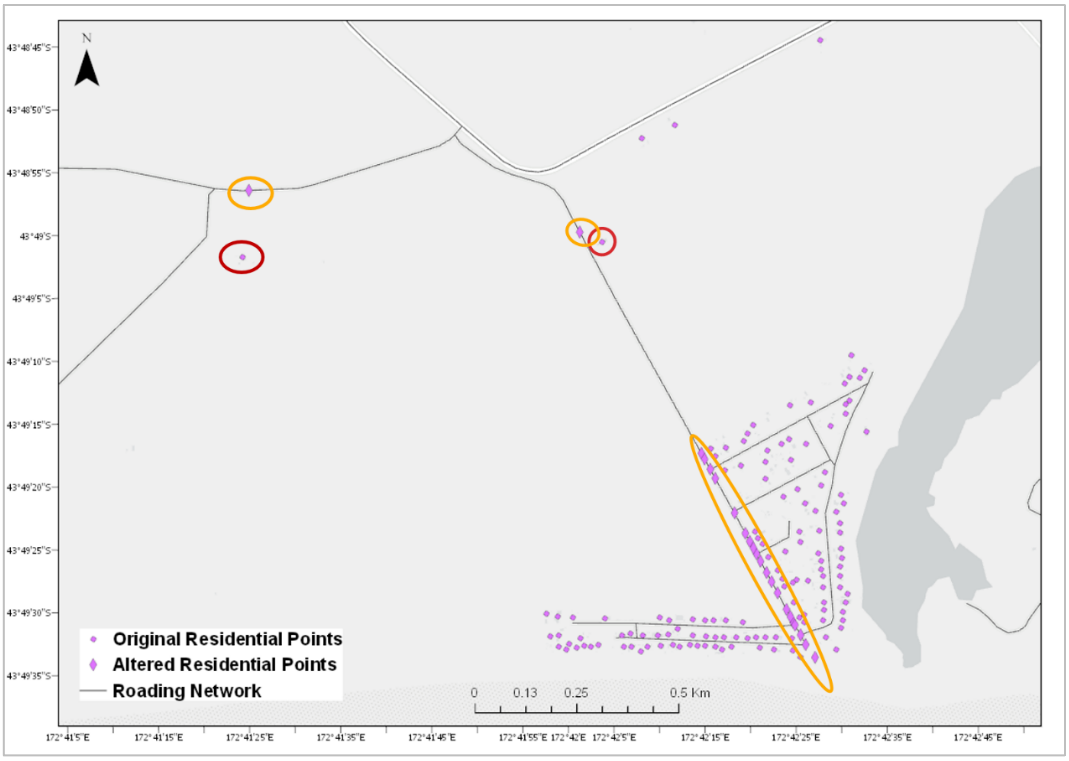

Figure 7.225: Original locations of input residential points for Birdlings Flat. Squares represent points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circles). The diamonds represent where the point were moved to ensure the model worked successfully (in the orange circles). Note that the entire township of Birdlings was not initially picked up by the modelling tool so points were relocated to Poranui Beach Road (shown in the large orange oval)

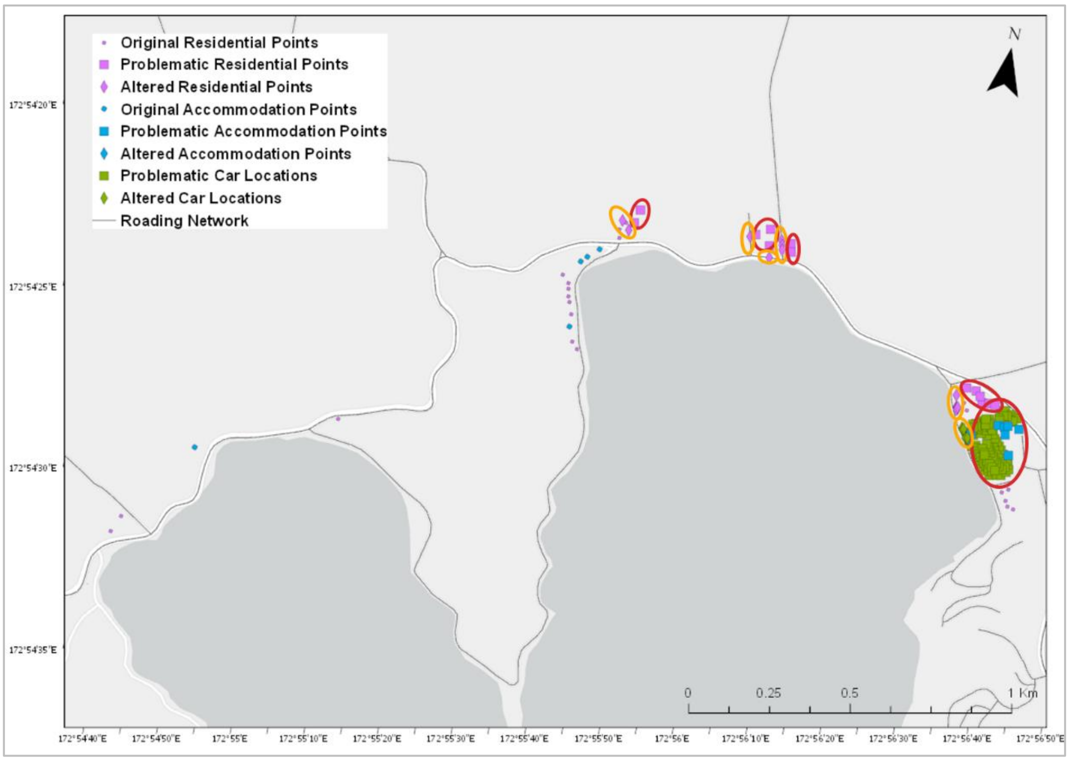

Figure 7.226: Original locations of input residential, accommodation and vehicle points for Duvauchelle. Squares represent points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circles). The diamonds represent where the points were moved to ensure the model worked successfully (in the orange circle). Note that all of the points at the campground (on the east of the map) were not initially picked up by the modelling tool so points were relocated.

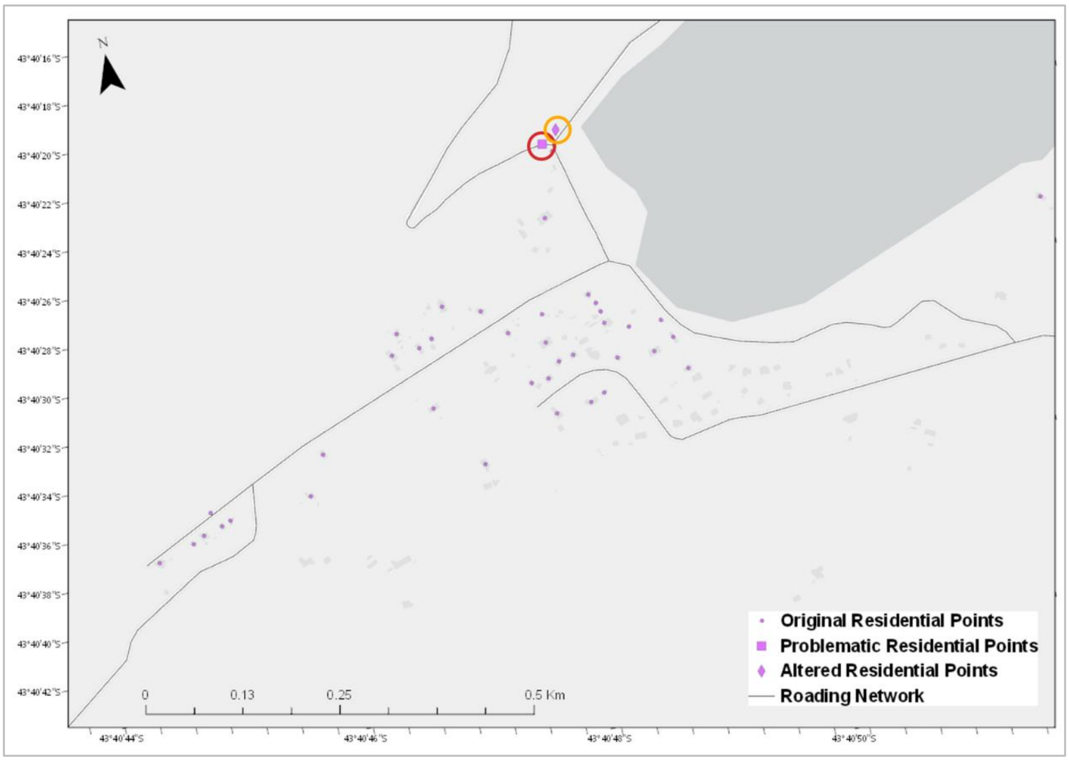

Figure 7.227: Original locations of input residential and accommodation points for Little Akaloa. The square represents points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circle). The diamond represents where the point was moved to ensure the model worked successfully (in the orange circle).

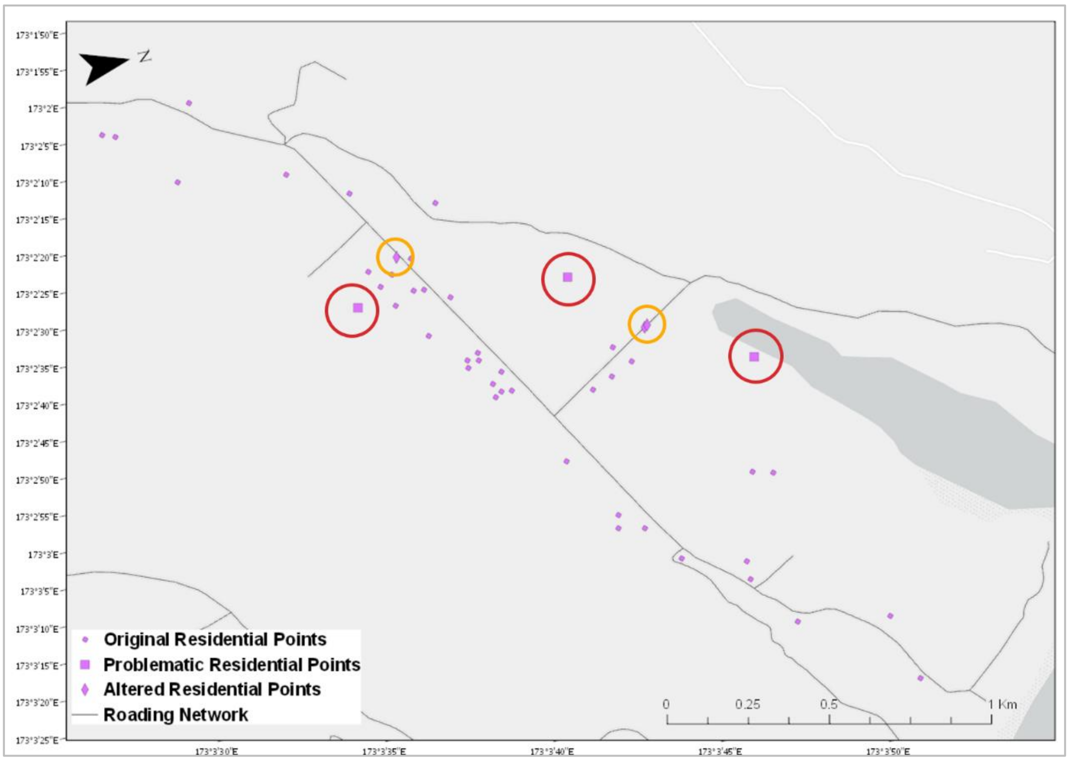

Figure 7.228: Original locations of input residential and accommodation points for Okains Bay. The squares represent points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circles). The diamonds represent where the points were moved to ensure the model worked successfully (in the orange circles).

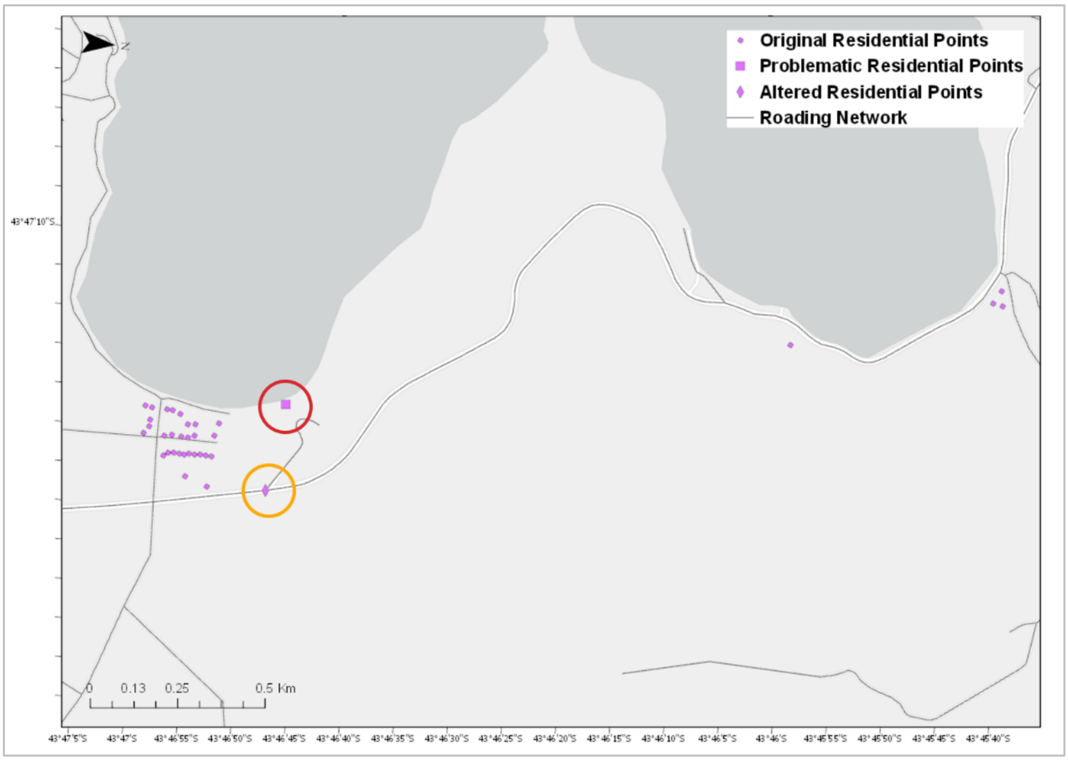

Figure 7.229: Original locations of input residential and accommodation points for Wainui. The square represents points that were problematic and not picked up initially by the model when solving the evacuation routing problems (in the red circle). The diamond represents where the point was moved to ensure the model worked successfully (in the orange circle).